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WRP Technical Note FW-EV-3.1
May 1994

Design and Application of a Larval Fish Trap

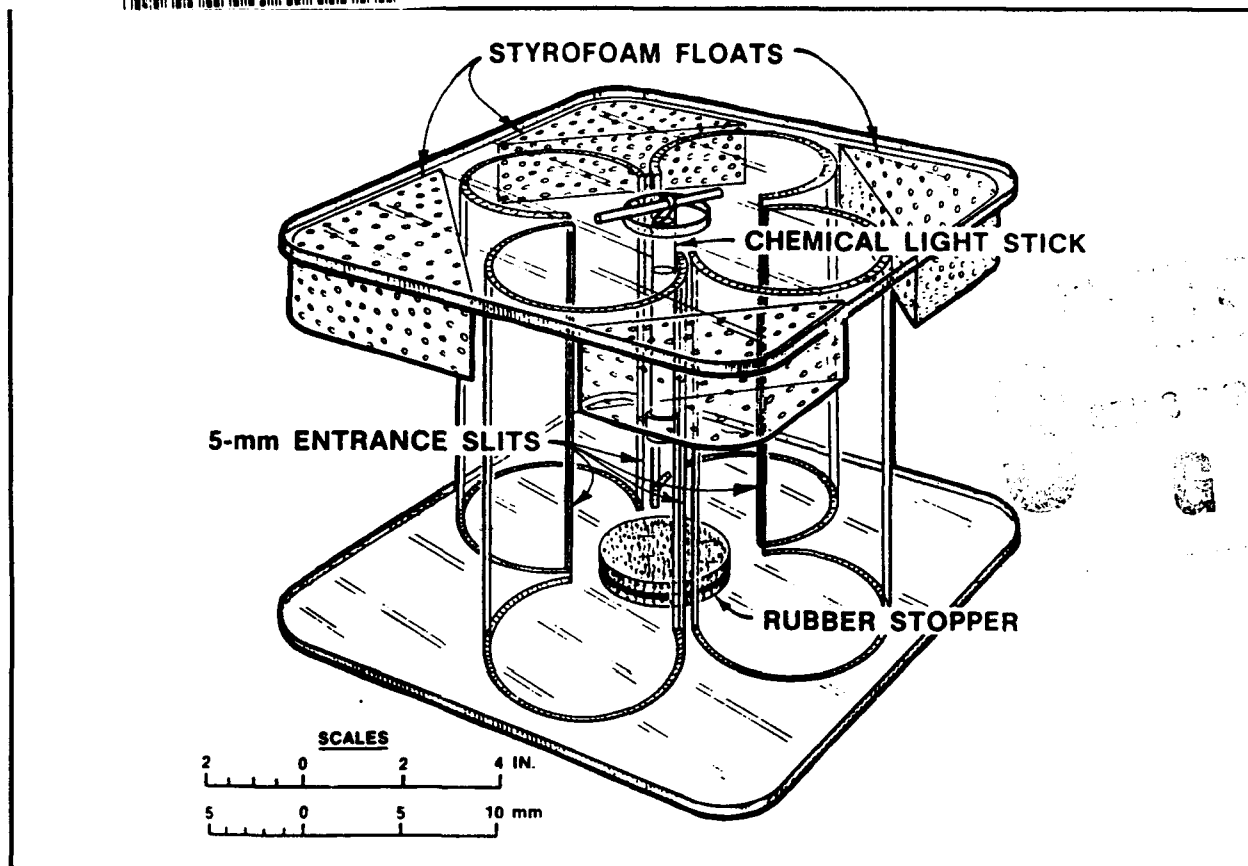


Figure 1. Larval Fish Trap

PURPOSE: This technical note describes construction of a light-activated Plexiglas trap used to collect larval fish. Since many fish are attracted to light, this type of collection method is useful to estimate abundance and to examine species composition of larval fishes. Light traps are ideal for sampling vegetated habitats such as wetlands and can be constructed in the laboratory or workshop.

DESIGN: The plan for the light trap (Fig. 1) is a modification of the Quatrefoil trap designed by Floyd et al. (1984). It is based on a slotted trapping system where four 5-mm entrance slots allow larval fish to enter the inner chamber. Once fishes are inside, they find it difficult to escape back through the narrow slots. One of the primary modifications to the original design is the use of a 12-hour, yellow Cyalume chemical lightstick for attracting fishes. This device eliminates the need for electrical power.

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The base and top of the trap are solid pieces of 64 mm thick Plexiglas measuring 30.5 by 30.5 cm. A 2.5-cm hole is cut into the top plate for inserting the chemical light stick. The hole also provides an area where the trap can be grasped with a finger during retrieval. A 10.2 cm hole is cut in the bottom plate where a rubber stopper or cod end bucket is inserted. A removable rubber flange stopper is most efficient because it provides a tight seal, is easily removed for quick retrieval of larval fishes, and is readily available from plumbing supply stores. Four Plexiglas cylinders are cut longitudinally. Each tube is made of 64 mm thick Plexiglas and is 15- to 30 cm long. All four cylinders are glued to the top and bottom plates of Plexiglas with epoxy, allowing a 5 mm entrance slit between each cylinder.

Styrofoam is affixed to each corner of the top plate with epoxy, allowing the submersed trap to float on the water surface. A 2 mm hole is drilled into the top plate and a string is tied to the trap. The string is attached to a tree or stake to prevent the trap from floating away. If the trap cannot be tied off, an anchor line can be attached through a small hole drilled into the bottom plate. The cost per trap is relatively low (approximately \$50).

TRAP APPLICATION: At least 30 traps can be transported to a sampling site in a 3-m canoe or flat bottom boat. Light traps are usually set at dusk and fished for predetermined time periods in order to derive catch per unit effort (CPUE). Traps are placed in the water with the activated light stick inserted into the trap.

After a preset time period, the boat is carefully brought up to the light trap and a plankton net is slowly positioned under the trap. The trap is gently lifted and the stopper removed. After the trap is washed several times to transfer fishes into the plankton net, it can be stored on the boat or placed back into the water for later pickup or resetting. The contents of the trap are washed through the plankton net into a cod end bucket attached to the net and fishes are transferred into a jar for preservation.

Depending on the needs of the experiment, light traps can be set at discrete depths to determine vertical occurrence of fishes. Dimensions of the trap and width of the entrance slits can be modified to meet various experimental requirements. For example, shorter traps (e.g., 15 cm long) are easier to transport in small boats and to sample shallow water.

SAMPLING CONSIDERATIONS: Light traps are a passive capture technique in that they remain stationary during the sampling period. If there is no water flowing through the trap, the water volume sampled is equivalent to the transmittance of light through the water column that is detectable and recognized by a stationary or moving phototactic fish. Turbidity and meteorological conditions affect light transmission. In addition, the phototactic behavior of larval fish, their temporal and spatial abundance, and the type of hydraulic regime in the sampling area directly influence encounter and collection rates. These factors result in considerable variation in catch using light traps and high sample sizes are required to reduce the variance.

Darters (*Family Percidae*), pirate perch (*Aphredoderidae*), minnows and shiners (*Cyprinidae*), and sunfishes (*Centrarchidae*) are best represented in light trap catches overall. The maximum number of larval fish collected in any one trap was over 2,000. Light traps have been successfully used to collect larval fish in riverine floodplains and littoral zones of reservoirs colonized by submersed aquatic plants. When spawning and rearing of fishes are components of environmental studies, light traps can provide life history data for many species of fish.

**The WRP Notebook
Issued May 1994**

Directions

1. Preliminary pages. Replace pages ix and x. Add page xi.
2. Section FW: Fish/Wildlife. Place Technical Notes FW-EV-3.1, FW-RS-7.1, and FW-SW-4.1 after FW-EV-2.2.
3. Section HS: Hydraulics. Place Technical Note HS-CP-5.1 before HS-EM-3.1.
4. Section HY: Hydrology. Place Technical Notes HY-IA-2.1 and HY-IA-2.2 after HY-EV-5.1.
5. Section SD: Sedimentation. Place Technical Notes SD-CP-2.1, SD-CP-2.2, and SD-CP-2.3 before SD-CP-4.1.
6. Section SG: Soils/Geology. Place Technical Notes SG-RS-1.1 and SG-RS-1.2 before SG-RS-3.1.
7. Section VN: Vegetation. Place Technical Note VN-DL-1.1 after VN-CP-4.1.
8. Section WQ: Water Quality. Place Technical Note WQ-SW-3.1 after WQ-EV-2.1.
9. Section WG: Wetlands-General. Place Technical Notes WG-EV-2.1 and WG-EV-2.2 before WG-EV-6.1. Place Technical Notes WG-SW-2.1, WG-SW-2.2, and WG-SW-2.3 after WG-RS-3.1.
10. Replace index with new index pages.
11. File this sheet after sheet iv-5 to show that this notebook copy is up to date.

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Technical
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CONCLUSION: The information presented allows construction of light attributed fish traps and explains the best methods for their use in data collection/sampling.

REFERENCES:

Floyd, K. B., R. D. Hoyt, and S. Pimbrook. 1984. Chronology of appearance and habitat partitioning by stream larval fishes. Transactions of the American Fisheries Society 112: 280-285.

Killgore, K. J. and R. P. Morgan II. 1993. "Easily constructed light trap helps scientists collect larval fishes in wetlands." WRP Bulletin, Vol 3, No. 4, pp 1-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

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*Per Jack Killgore
10/6/94*



Weaver Bottoms Wildlife Habitat Restoration: A Case Study

PURPOSE: This technical note evaluates the success of a wetland rehabilitation project in the first four years following construction. Backwater areas of the Upper Mississippi River provide important feeding and resting areas for migratory waterfowl, and habitat quality deterioration of these highly productive marshes has been a cause of great concern. The Weaver Bottoms Rehabilitation Project is a large scale wetland restoration project that is directed at regaining lost habitat by creating hydrological and energy conditions conducive to marsh growth and production. Davis et al. (1993) presents the Phase I pre-project (1985-87) and post-construction (1988-91) monitoring results and assesses project impacts on the Weaver Bottoms aquatic system during the first three years following construction. This technical note summarizes that report.

BACKGROUND: In the early 1930's, the U.S. Army Corps of Engineers constructed a series of locks and dams in the Upper Mississippi River to improve commercial navigation along the 848 river miles from Cairo, IL to Minneapolis, MN. Extensive areas of the UMR's floodplain were inundated and rapidly became highly productive backwater marshes. Since the early 1960's, however, aerial coverage and density of wetland vegetation have fluctuated and gradually declined, reducing many backwater marshes to open, windswept, riverine lakes with low fish and wildlife habitat quality.

The Great River Environmental Action Team I was organized in 1973 with representatives from the Army Corps of Engineers, U.S. Fish and Wildlife Service, Wisconsin, and Minnesota to identify and assess the problems associated with multipurpose use of the UMR and to develop recommendations for improved management of its resources. Weaver Bottoms, a 4,000-acre backwater area in Pool 5 of the UMR located between southeastern Minnesota and southwestern Wisconsin, was selected as a representative area for extensive study. It was determined that habitat quality deterioration was due to loss of marsh vegetation. The inability of marsh vegetation to recover was attributed to a variety of reasons, including two major floods in the late 1960's, uprooting and removal of plants by wind and ice, changed flow and sedimentation patterns, and reduced water clarity caused by wind-induced wave resuspension of sediments.

As a result, the Weaver Bottoms Rehabilitation Project was designed to reduce Mississippi River flows entering the backwater by modifying side channels and to reduce wind fetch and re-suspension of bottom sediments by creating barrier islands. Also, the project was to reduce maintenance dredging requirements in the navigation channel and provide long-term dredged material storage. Phase I construction at Weaver Bottoms was completed by mid 1987. Partial or complete closures were constructed across most of the secondary channels leading from the Mississippi River into the area with two 16-acre islands constructed in open waters (Fig. 1). Phase II will be implemented after the effects of Phase I construction have been evaluated.

A comprehensive, 10-year Resource Analysis Plan outlines how to monitor these Phase I project effects. The plan is based on an interagency Memorandum of Understanding, designating the U.S. Fish and Wildlife Service as the lead agency and providing for active participation from the U.S. Army Corps of Engineers, and Wisconsin and Minnesota Departments of Natural Resources.

MONITORING RESULTS: The Resource Analysis Plan established a 10-year monitoring program to assess project impacts on hydrodynamics, sedimentation, water quality, emergent and aquatic vegetation, use of aquatic and wildlife habitats by birds, fish, and mammals, and recreational use. Results from the first 6 years (1986-1992) of the monitoring program are summarized below.

- **Hydrodynamics.** Monitoring indicated that secondary channel discharges to Weaver Bottoms were reduced 80 percent, and hydraulic residence time was increased 2 to 6 times (from 3 days to 7.6 days in isolated portions) after construction. Current velocities within Weaver Bottoms have been reduced a similar order of magnitude (60-90 percent). The two constructed islands have altered flow patterns; but wave action continues to be a major factor influencing bottom velocities and sediment resuspension. Hydrodynamic impacts of the islands on Weaver Bottoms are small compared to the reduction in inflow due to closure of secondary channels.

There was concern that diversion of flow from Weaver Bottoms would adversely affect adjacent areas of Pool 5. Data indicate that for total river discharges less than 60,000 cfs (greatest flow during the monitoring period), secondary channel discharges, current velocities, and water surface elevations in areas outside of Weaver Bottoms have not been affected.

Overall dredging requirements in the navigation channel near Weaver Bottoms have decreased by 60 percent following project construction. The decrease in dredging requirements during the study period was probably due to greater channel scouring with increased river flows diverted from Weaver Bottoms into the main river channel.

- **Sedimentation.** Bathymetry data were collected pre-project in 1986 and post-project in 1991; 1935 data were also used in the analysis. Construction resulted in notable changes in erosion/deposition patterns in Weaver Bottoms. Although the net change in bathymetry from 1986 to 1991 was small, high rates of both deposition and erosion occurred, indicating that internal factors such as wind generated wave action have increased their influence on the sedimentation patterns in Weaver Bottoms.

General patterns show deposition in deep areas and erosion in shallow areas. Three areas showed the greatest change in bathymetry since project construction. First, the Pritchard Maloney area (Fig. 1), that historically has shown substantial erosion since inundation, has now become a depositional zone, with water depths reduced from a mean of 108 to 90 cm. Second, the delta areas at side channel openings along the main channel side of Weaver showed both deposition and erosion. For instance, from 1986 to 1991 as much as 90 to 120 cm of deposition occurred near remaining inlets to Weaver Bottoms; however, there was erosion of downstream portions of the inlet deltas. The other area that showed a great deal of change was near the mouth of the Whitewater River. In a 1990 Whitewater River study, increased rates of delta expansion were found to be a function of reduced flow velocities into Weaver Bottoms following project construction.

Sedimentation rates from 1935 to 1986 were estimated between 0.18 to 0.22 cm/year, with a net loss in water volume between 12 to 13.8 percent. Limitations with 1991 bathymetric data did not allow for a comparison of post-project sedimentation rates.

- **Water Quality.** A project objective was increased water clarity for improved conditions for vegetation growth, however, neither suspended solids or turbidity levels were reduced. Reduction of inflow from the Mississippi River reduced mixing and flushing rates in Weaver Bottoms. Water quality in downstream portions of the backwater area became more influenced by the Whitewater River, a turbid river which empties directly into Weaver Bottoms (Fig. 1). Variation

(heterogeneity) in water quality values increased among areas within Weaver Bottoms after project construction. Water quality in Weaver Bottoms did not improve within the first 3 years following construction. Completion of the 10-year monitoring program will allow better determination whether this project-induced heterogeneity is long or short term.

- **Vegetation.** Between 1985 and 1990, a general decline in emergent and submergent aquatic vegetation was recorded in the Weaver Bottoms Rehabilitation Project area. Total emergent vegetation biomass decreased from 4069 g/m² in 1985 to 1151 g/m² in 1990. Mean above ground wet weight for submergents decreased from 1404 g/m² in 1985 to 5 g/m² in 1990. The cause of the vegetation loss is unclear but is apparently related to the 1987-89 drought and not due to project construction. Drastic vegetation losses similar to those documented in this study have been noted in Pool 7 and other Upper Mississippi River pools during the same time period.
- **Birds and Mammals.** Aerial waterfowl transect surveys were conducted each fall from 1985 through 1990. Peak waterfowl numbers usually occurred on Pool 5 in late October. Waterfowl use-days increased substantially between 1986 and 1987, but sustained a steady decline during the remaining post-construction period of 1988-90. Annual diving duck (mostly canvasback, *Aythya valisineria*) use-days were more than double that of puddle ducks during the 1985-87 period, but were below or nearly equal to puddle duck use-days 1988-90. This post-construction decline in diving duck use probably reflected the drastic losses of American wildcelery (*Vallisneria spiralis*), a preferred canvasback food, in Weaver Bottoms during 1989 and 1990. Total use-days of tundra swan (*Cygnus columbianus*), another common migratory waterfowl in the area, varied but were lowest in 1989 and 1990 when substantial declines in arrowhead (*Sagittaria* spp.) biomass were detected.

The waterfowl and vegetation declines at Weaver coincide with those observed on Pool 7 where wildcelery acreage plummeted from 3,500 acres in 1987 to less than 300 acres in 1989. Losses in vegetation and waterfowl use on the Weaver Bottoms project area were not attributable to the rehabilitation project, as evidenced by similar losses in nearby Upper Mississippi River pools. Changes in continental populations, habitat conditions, and weather influenced migratory bird use of the river. The occurrence of muskrat (*Ondatra zibethica*), shorebirds, gulls, and terns on Weaver Bottoms was monitored but no population trends were detected.

- **Fish.** Fish populations were monitored within and outside the Weaver Bottoms project area. Trap nets, experimental gill nets, and electroshocking methods were used. Pre-construction sampling yielded 9,323 fish representing 69 species with an average weight of 264 g/fish. Post-construction sampling yielded 16,992 fish, representing 57 species with a higher average weight of 271 g/fish. All sample methods showed an increase in catch per unit effort during the post-construction years. The proportion of sport fish, rough fish, and forage fish captured, showed little change between pre- and post-construction periods.

	By Number		By Weight	
	Pre	Post	Pre	Post
Sport fish	56%	61%	34%	32%
Rough fish	23%	22%	62%	66%
Forage fish	21%	17%	2%	2%

Proportions of fish initially caught during the pre-project and post-construction Weaver Bottoms RAP monitoring program represented by major guilds of the Upper Mississippi River.

Four species were identified as key species in the Weaver Bottoms Resource Analysis Plan: northern pike (*Esox lucius*), carp (*Cyprinus carpio*), bluegill (*Lepomis macrochirus*), and black crappie (*Pomoxis nigromaculatus*). Gill netting data show a biomass increase for all four species in the post-construction period with carp increasing the most. Similar increases in catch per unit effort for the four species at stations within and outside Weaver Bottoms indicate that population increases may be partially due to factors other than the rehabilitation project.

- **Recreation.** Estimates of recreational activity in Pool 5 were made by passive observations at water recreation accesses to Pool 5, boat patrols counting visitors, aerial surveys, and use of recreational lockage figures in 1986, '87 and '89. The Weaver Bottoms project has had little detectable effect on recreational use of Pool 5 thus far. A few new beaches created at closures attract some use.

CONCLUSIONS: Although the findings from the Weaver Bottoms Resource Analysis Program presented in this technical note are preliminary, several important results can be used to improve future efforts to restore river backwater areas. The first outcome of this project indicates the need to identify and treat all causes of habitat degradation to facilitate natural recovery. Wind and current energy in Weaver Bottoms clearly caused physical damage to the plants as well as turbid water, but there were other factors that contributed to the vegetation decline. The plants were unable to recover in Weaver Bottoms after project construction because they were continually weakened by additional stresses such as carp and pesticides in agricultural runoff. In addition, natural developmental phases of a continuously inundated marsh include senescence of the emergent aquatic vegetation that is not able to regenerate by seed and the subsequent development of open water, like what happened in Weaver Bottoms. If all stresses and the natural ecology of the potential restoration site are considered, a combination of treatments may be more effective than concentrating on one factor. In the case of Weaver Bottoms, effective restoration may require active intervention such as water level manipulation to encourage revegetation or planting of desired species. It is likely, however, that carp must be controlled until the vegetation is fully established. Moreover, additional structures may be required, as was outlined for Phase II of the project, to reduce further fetch and wave energy.

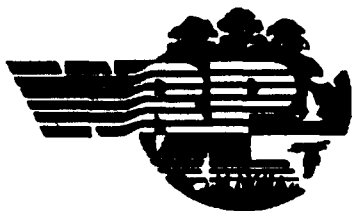
In addition to thorough identification and treatment of causes of degradation, the degree of degradation of the site must be considered. Weaver Bottoms had lost most of the emergent vegetation before construction of the rehabilitation project. Regardless of the causes, it is more difficult to restore habitat quality of a severely degraded site than a less degraded site. When natural processes of the functioning ecosystem are lost, it is very difficult to reestablish the complex interrelationships of factors that support those processes. Although it is not advisable to rush into an extensive restoration project without thoroughly investigating the causes of degradation, it is equally inadvisable to begin restoration efforts when the site has lost the capability to recover. Restoration measures will be much less extensive and costly if restoration efforts are applied as early as possible after degradation of the site has been identified and is most easily reversed.

REFERENCE: Davis, Mary M., Nelson, Eric, Burns, Carol, editors. 1993. The Weaver Bottoms Rehabilitation Project Resource Analysis Program: Interim Report (1985-1991). U.S. Fish and Wildlife Service, Winona, MN.

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Guidelines for Placement and Management of Wood Duck Nest Boxes in Wetland Habitats



PURPOSE: This technical note provides recommendations for the location and management of nest boxes to supplement natural nest sites in a variety of wetland habitats for wood duck (*Aix sponsa*). The wood duck is associated with forested wetlands throughout much of the United States and is a common resident at Corps of Engineers reservoir projects.

BACKGROUND: Since wood ducks are cavity nesters, they are closely associated with wetland habitats where there is an abundance of snag trees and natural cavities. However, birds will readily accept specially made boxes constructed of wood, metal, or plastic in areas where the lack of suitable nest sites is responsible for limiting increases in breeding wood duck populations. Such settings include reservoir backwater areas, tributary streams, tailwater areas, subimpoundments, abandoned sand or gravel pits, oxbow lakes, and beaver ponds.

Nest box programs have been established throughout the United States with approximately 5 percent of the juvenile component of the fall flight population of wood ducks attributable to production in boxes. Nest box programs have yielded a set of general criteria that will increase the chances of success for a nest box project. These fall into three general categories: (1) nest box placement, (2) predator management, and (3) monitoring and maintenance.

PLACEMENT: Ideal nesting and brood-rearing habitat for wood ducks consists of shallowly flooded areas with an interspersed of flooded trees and shrubs, emergent and floating vegetation, and open water areas. Before implementing a wood duck nest box program, a survey should be conducted to determine the adequacy of natural cavities and to assess brood-rearing habitat. If the current nesting population is high, the efficacy of a nest box program should be questioned. Areas smaller than 4.0 ha are usually considered marginal as brood-rearing habitat if they are separated by more than 46 m

of land. However, complexes of beaver ponds and/or small streamside areas are acceptable if the individual units are interconnected by water corridors.

- **Height.** Nest box height is still debated among researchers and managers. Several studies have shown that nest sites >9 m above ground are more acceptable to wood ducks than are lower sites. However, a recent study in Alabama showed that when wood ducks were given a choice of three boxes at different heights on the same tree, they selected the lowest (2.0 m above ground) 54 percent of the time. Boxes located at heights of 3.8 m and 5.6 m were used at rates of 24 and 22 percent, respectively. The lowest boxes also had higher nest success (60 percent) than the higher boxes (50 percent and 45 percent) in this study. Boxes will generally need to be located higher in areas subject to flooding. Experimentation with box placement to determine the optimum heights to attach boxes may be necessary.

Wood ducks prefer boxes located over water and duckling survival increases the less distance they must travel over land to reach brood-rearing sites. Boxes placed over water are also less subject to predation. If it is not feasible to place boxes over water, they should be located as close to potential brood-rearing habitat as possible.

- **Orientation.** The orientation of the boxes' cavity opening appears to have an effect on wood duck use. Ducks prefer cavities with entrances directed toward the nearest forest opening in both upland and bottomland habitats. Cavities that are readily visible from the path of nest-searching females (in flight or swimming) are apparently used at a higher rate. Placement of boxes with the entrance oriented away from nearby roads should also be considered. This would serve to reduce noise disturbance to the nesting female as well as minimize potential vandalism.

Boxes should be installed out of direct sunlight, since studies have shown that high temperatures can destroy eggs and result in nestling mortality. This is critical if plastic or metal boxes are being used, especially in the southern United States. Cypress boxes are found to be significantly cooler than plastic boxes exposed to the same conditions.

- **Density.** As the breeding density of wood ducks increases, box occupancy, clutch size, and the occurrence of dump nesting increases. Dump nesting (also referred to as nest parasitism) is the condition where a nest site receives eggs from many females (hatching success in these nests is usually zero); the incidence of dump nesting is greatest where there are high population densities.

Dense breeding populations coupled with high box visibility and closely spaced boxes will lead to high rates of nest parasitism. When boxes are installed, they should be placed singly in visually isolated sites, which would reduce the opportunity for females to observe other wood ducks at active sites. Although this strategy might reduce occupancy rates, it should reduce nest parasitism, increase nesting success, and encourage high productivity.

PREDATOR MANAGEMENT: Wood duck nest losses from artificial boxes are generally higher than for natural cavities because predators will quickly learn to associate boxes with an easy meal. Commonly reported predators of wood duck nests and hens include the great horned owl (*Bubo virginianus*), raccoon (*Procyon lotor*), bobcat (*Lynx rufus*), squirrels (*Sciurus* spp.), red-bellied woodpecker (*Melanerpes carolinus*), European starling (*Sturnus vulgaris*) and snakes. Raccoons especially have been reported to seek out boxes and will frequently enter every box on a management area during a single feeding period. Some predators reportedly develop a "search pattern" directed toward locating boxes. A nest box program should not be implemented without ensuring that predator guards

and/or other protective devices are used to prevent the boxes from becoming death traps. Snakes can be especially significant predators on wood ducks, and most snakes found inside boxes have been reported to consume the entire clutch. Rat snakes (*Elaphe* spp.) are usually implicated as having the greatest impact on wood duck nestlings. It is very difficult to exclude snakes from boxes because those that are at least 1.7 m in length can bypass most predator guards or can drop into boxes from overhanging limbs. The application of a sticky material on structures supporting duck boxes has been used to reduce snake predation. This approach may not be cost effective in large nest box programs.

Several types of predator guards can protect boxes. These include aluminum bands, metal cones, and similar devices. Special entrance hole designs have been used to exclude raccoons. Predation can also be discouraged by installing boxes on poles over water or by mounting them on bent metal brackets that extend approximately 0.6 m from a tree or post.

BOX MONITORING AND MAINTENANCE: Maintenance and monitoring of nest boxes is essential to a successful program. Depending on the size of the nest box program, complete checks or a random sampling of boxes can help in estimating the number of breeding pairs in an area. If possible, this information should be supplemented with data from harvest records maintained by state agencies and the U.S. Fish and Wildlife Service.

When developing a wood duck nest box survey program, basic information on each nest box installed at the project should be collected into a file. A standardized fact sheet should be prepared for each box; this sheet should contain at least the information shown in Figure 1.

Areas with nest boxes should be given a site number within a compartment, or other defined location, and a number should be inscribed on each box to facilitate record keeping. Managers can identify and move boxes from unproductive sites and maintain those that are successful. The numbering system will also facilitate handling of data. Ideally, boxes should be numbered sequentially as they are installed. It is recommended that fact sheets be filed according to site within each compartment.

At a minimum, wood duck nest boxes should be inspected twice a year. A maintenance check of all boxes should be made each winter, usually no later than mid-January, beginning with a pre-nesting check of all boxes to replace or repair those that are damaged. Additionally, old nesting material and egg shells should be removed, and boxes should be treated with a disinfectant to reduce ectoparasite problems. Wood shavings or sawdust should be added to a depth of 10 to 16 cm to provide a proper nesting substrate. Timing of pre-nesting box maintenance must precede the normal nest initiation dates.

Box use should be assessed soon after the ducklings have left the nest. During this inspection, data should be collected on wood duck use, including number of eggs and number of eggs hatched, and use by other species. Boxes not used and box failures should also be noted. If possible, the reason for box failure (e.g., abandonment, predation, flooding, human disturbance) should be indicated. These data should be compiled for each site on the inspection sheet (Fig. 2). It may be possible to inspect only a sample of boxes at each site during the summer survey period due to time and personnel constraints.

An annual summary report of wood duck nest box use should be filed with the District. The following information should be displayed for each site: habitat type; total number of boxes at the site; the survey sample size; and the number and percentage of boxes not used, boxes failed, wood duck use, other use, and total use.

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NEST BOX FACT SHEET

Compartment # _____ Site # _____ Box # _____

Location _____
(include map for each site showing precise location of boxes)

Habitat Code _____ Site Description _____

Box Type (wood, plastic, metal, etc.) _____

Type of Support _____
(tree, wooden pole, metal pole, etc.)

Height of Base Above Water _____

Predator Guard (Y/N) _____ Type of Guard _____

Box Exposure _____
(shaded, partly shaded, full sun)

Direction of Hole Entrance - N NE E SE S SW W NW

Date Installed ____/____/____ Installed by _____

Annual Inspection Record:

<u>Date</u>	<u>Box Condition and Comments</u>
____/____/____	_____
____/____/____	_____
____/____/____	_____
____/____/____	_____
____/____/____	_____
____/____/____	_____
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Figure 1. Fact Sheet

[illegible]

5

CONCLUSIONS: Wood duck nest boxes are a useful management tool in areas that contain good brood-rearing habitat but are deficient in natural nest sites. Although a wood duck nest box program can increase local production, the proper preservation and management of bottomland hardwoods and associated wetland habitats are most critical to the well-being of wood duck populations. Management for natural cavities should be encouraged as much as possible.

ADDITIONAL RECOMMENDED READING:

Bellrose, F. C. 1980. Ducks, geese and swans of North America, Third ed., Stackpole Books, Harrisburg, PA.

Dugger, K. M., and Fredrickson, L. H. 1992. "Life history and habitat needs of the wood duck," U.S. Fish and Wildlife Service Waterfowl Management Handbook, Fish and Wildlife Leaflet 13.1.6.

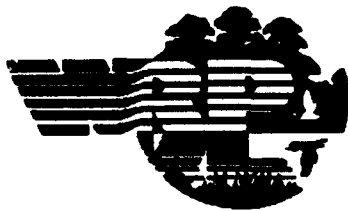
Fredrickson, L. H., Burger, G. V., Havera, S. P., Graber, D. A., Kirby, R. E., and Taylor, T. S., eds. 1990. *Proceedings, 1988 North American Wood Duck Symposium*, St. Louis, MO.

Lacki, M. J., George, S. P., and Viscosi, P. J. 1987. "Evaluation of site variables affecting nest-box use by wood ducks," *Wildlife Society Bulletin*, 15, 196-200.

Ridlehuber, K. T., and Teaford, J. W. 1986. "Wood duck nestboxes: Section 5.1.2, U.S. Army Corps of Engineer Wildlife Resource Management Manual," Technical Report EL-86-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS

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Userguide for the Wetland Water Budget Model Tutorial

PURPOSE: This technical note provides step-by-step instructions for using a computerized tutorial to help set up, execute, and calibrate the Wetland Water Budget Model, and to help manipulate the model's output using a post-processing program.

BACKGROUND: The Wetlands Research Program has developed a water budget model which can be used to model hydrologic and hydraulic processes in wetlands, and is a useful tool for investigating wetland functions. The model is modular in design, allowing users to run only those modules important to their study. For example, if users are interested in surface water processes, they would run the surface water module. The model also has a horizontal groundwater flow module and a vertical processes module (for precipitation, canopy interception, infiltration, and evapotranspiration). Any combination of the modules can be selected by the user. The number of input files (and the amount of data) needed to run the model depends on which modules are selected. A user could quickly become confused over which input files are needed and what data are required. To eliminate the confusion, a screen-driven, PC-based tutorial was developed to help users select modules, identify all of the necessary input files, and to give users instructions for formatting the data in those input files. The program also provides instructions for calibrating and running the water budget model, and manipulating the model's output.

For more information about the water budget model (including the processes it models, applications of the model, and assessments of the model's capabilities), the tutorial program and a program for manipulating output data, see Walton and Chapman (1993).

OVERVIEW: The computerized tutorial for running the water budget model uses a sequence of screens to prompt users for information they need for their particular model application. The following is an overview of the screens.

SCREEN 1: Provides instructions for using the screens. To move the cursor around a screen, use the **TAB** or **ARROW** keys. To move from one screen to the next, use the **Page Up/Down** keys. Use the **Enter** key to make selections within screens and the **Control_H** keys to obtain "Help" at any time.

SCREEN 2: Permits users to select one or more of the water budget model's modules for their particular application, and allows them to define a **project name** (less than 9 characters) which becomes the "root" name for all of the input and output files.

SCREEN 3: Identifies the necessary input files required for the particular application (set of modules) selected by the user. The necessary files are indicated by a "YES" appearing in the box next to the file name. Users can view examples of the format for a file's data by selecting (**Enter** key) the file while the cursor is positioned by the file name. The user can also get more information regarding data sources by pressing the **Control_D** keys. The names of the output files that the water budget model will generate are identified by the word "OUT" next to the file name. The "MAKE

FILE option will automatically generate a file list (called "root") which the water budget model uses to identify which files are input files and which are output files.

SCREEN 4: Tells the user how to setup the input data, calibrate and run the model, and manipulate the output data. When the user exits this screen, the tutorial ends. The user may also exit the tutorial at any time by pressing the END key.

The remainder of this TN concentrates on the module components of the tutorial.

SURFACE WATER MODULE SELECTION: By selecting the surface water module (from SCREEN 2) for their model application, users can simulate surface water processes such as channel flow, over-bank wetting and drying, remote-basin inflow, tidal forcing, local rainfall and wind forcing. SCREEN 3 of the program will enable the following file names (i.e. a "YES" will appear next to the file names in SCREEN 3):

- root.OUT** - general output file to which model input and run information are output.
- root.PAR** - run parameter file where module selection; simulation start date, duration, time step; print initiation and interval; and echo print options are given.
- root.GRD** - grid file where the number, location, size, and shape of nodes and links; the linkage between nodes; and link elevation, inverse side slope, and type are defined.
- root.ELV** - contains the bottom and overbank elevations of each node.
- root.PRP** - defines link properties such as friction formulation, and weir and culvert coefficients.
- root.INI** - specifies the initial nodal stages or water elevations above the model datum.
- root.BCI** - specifies the upstream and downstream boundary conditions (e.g. stage, flow, loop rating, or stage-discharge).
- root.HBC** - time series of stages or surface water elevations at each head boundary node specified in file "root.BCI."
- root.FBC** - provides the time series of flows or discharges at each flow boundary node specified in file "root.BCI."
- root.MET** - contains daily meteorological inputs such as rainfall, temperature, solar radiation and wind speed and direction.
- root.HDS** - nodal head or elevation output file.
- root.FLO** - link flow or discharge output file.
- root.VOL** - nodal volume output file.
- root.VEL** - link velocity output file.

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When in SCREEN 3, examples of the input files may be viewed by moving the cursor to the box next to the file of choice and pressing the ENTER key. A sample input file is displayed showing the free-field file format, file delimiters, and a description of each variable within a "Help" window at the bottom of the screen. While a sample input file is being displayed, pressing Control_D will display brief information on possible data sources for the necessary file data. The "Make File" option generates a file called "root" that contains the file names of all the input and output files required for a surface water module simulation.

Note: While examining the data structure for "root.GRD," the user can press the Control_F keys to display schematics of the geometry used to describe nodes or links. The figures will be displayed in conjunction with the appropriate line in the data file "root.GRD."

VERTICAL PROCESSES MODULE SELECTION: By selecting the vertical processes module (from SCREEN 2) for the model application, users can simulate processes such as canopy interception, ET, and infiltration. To prescribe inputs and boundary conditions for these processes, the following files are enabled (i.e. a "YES" will appear next to the file names on SCREEN 3).

- root.OUT** - general file to which input and run information are output.
- root.PAR** - run parameter file where module selection; simulation start date, duration, time step; print initiation and interval; and echo print options are specified.
- root.GRD** - grid file where the number, location, size, and shape of nodes and links as well as the linkage between nodes are defined.
- root.ELV** - bottom and overbank elevations of each node, and the elevations of the bottoms of each layer at each node.
- root.NOD** - canopy and soil types used in each node layer at each node.
- root.CAN** - canopy type in terms of drainage parameters and monthly values of leaf area index (LAI).
- root.SOL** - soil type in terms of moisture parameters, hydraulic conductivities, and the power function relationship to soil moisture tension.
- root.INI** - initial nodal water surface elevations and groundwater heads in each layer, with respect to the model datum.
- root.MET** - daily meteorological inputs such rainfall, temperature, solar radiation, and wind speed and direction.
- root.HDS** - nodal surface water head output file.
- root.GWH** - nodal groundwater heads output file.
- root.SMC** - nodal soil moisture content output file.
- root.SUM** - vertical water mass balance file.

When in SCREEN 3, examples of the input files may be viewed by moving the cursor to the file of choice and pressing **Enter**. A sample file will appear showing the free-field file format, file delimiters, and a description of each variable within a "Help" window at the bottom of the screen. While the sample input file is displayed, pressing the **Control D** keys will show some general information on possible sources for the necessary file data. The "Make File" option generates a file called "root" that contains the file names of all of the input and output required for a vertical processes module simulation.

HORIZONTAL GROUNDWATER FLOW MODULE SELECTION: By selecting the horizontal groundwater flow module, users can include that hydrologic process in their application. The module can be used alone to simulate depth-averaged groundwater flow, although it is important to remember that the module is based on variably saturated groundwater flow theory. More commonly, the module would be used with the vertical processes module (described above) to simulate three-dimension groundwater flow and surface exchanges. In order to prescribe inputs and boundary conditions for these processes, the files "root.OUT," "root.PAR," "root.GRD," "root.ELV," "root.NOD," "root.SOL," "root.INI," "root.GWH," and "root.SMC" are enabled (i.e. a "YES" will appear next to the file names in SCREEN 3) as described above for the vertical processes module. In addition, SCREEN 3 enables "root.BCI" which specified fixed head boundary conditions and the location of wells.

MODEL EXECUTION: Once the necessary input data files are created, the selected modules are executed by typing "WWBM" followed by **Enter** at the DOS prompt. (Note: the prompt must be in the directory where the swamp program resides or the directory must be in the PC Path [see DOS manual].) At the program prompt, enter the 'control' file name: "root" followed by **Enter**. The program will echo the input and output file names and grid manipulation operations as they are completed. During the model simulation, the program prints a message to the screen each time output data are written. When "SIMULATION COMPLETED" appears on the screen, execution ends.

OUTPUT MANIPULATION: A post-processing program (called WWBMAID) is available with the water budget model. The program allows users to customize the output data from the surface water module output files. After starting the WWBMAID program, the following data manipulation options are displayed:

1. Create file with specified node numbers
2. Compare computed and observed heads
3. Compare computed and observed flows
4. Select a node or link for graphics
5. Edit heads for initial conditions
6. Convert grid files to new datum and units
7. Hydroperiod statistics
8. Water surface profiles
9. Add more columns of data to file
10. Groundwater heads for graphics
11. Calculate head from soil moisture content
99. EXIT

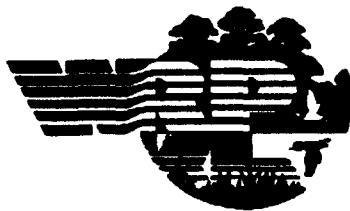
Enter selection:

CONCLUSION: A computerized tutorial is available to help users setup, calibrate, and run the Wetland Water Budget Model that simulates wetland hydrologic and hydraulic processes. The tutorial also explains how to use a post-processing program to manipulate the model's output data. The tutorial program, the Wetland Water Budget Model, and the post-processing program are available through the WES Engineering Computer Programs Library, Attention Gloria Naylor at (601) 634-2581. The programs' reference number is 722-PD-R0008.

REFERENCE:

Walton, R. and Chapman, R. S. 1993. "Development of an Integrated Hydrologic and Hydrodynamic Numerical Model for Wetland Processes and Function Evaluation," prepared for Coastal Engineering Research Center, USAE WES, prepared by Ebasco Environmental, Bellevue, WA, and Ray Chapman and Associates, Vicksburg, MS.

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Harmonic Analysis Can Assess Hydrologic Cumulative Impacts

PURPOSE: This technical note describes an aid for assessing cumulative impacts on wetlands. Harmonic analysis techniques are employed to reveal time-frames when disruption to basic flow patterns may have occurred.

BACKGROUND: Water-level patterns largely determine the nature of wetlands. Therefore, studies of historic water trends associated with wetlands should explain causes-and-effects operating on wetlands and the resulting landscape/ biotic composition. Keys to characterizing historic water-level trends are called "hydrologic indices."

SIMPLE INDICES SAMPLE: Hydrologic indices may be categorized as either simple or complex. Simple indices are easy to compute and include parameters such as mean, median, and range of flows. However, these indices often fail to describe adequately periodicity, seasonal behavior, or evolution of stream character resulting from land-use changes and channelization.

Despite obvious limitations, such simple indices can reveal important features of streamflow and how those parameters compare with those of other streams in the same basin. These simple indices can also give clues regarding the timing of historic, momentous events, such as the abrupt decrease of the monthly maximum flow in the Little Red River record (1961) shown in Figure 1 with records of other selected streams in the White River Basin (Arkansas/Missouri).

The effects of more subtle but perhaps no less profound impacts may be better detected and quantified using indices that are somewhat more complicated to derive but which may yield more insight into cumulative impact analysis. One such index investigated, harmonic analysis, is given here. Another index, time scale analysis, is treated in WRP Technical Note HY-IA-2.2.

HARMONIC ANALYSIS INDEX: Harmonic analysis can show not only periodicity but also the change of a stream's character ("flashiness," ratio of minima to maxima and means, etc.) over time. This index reveals seasonal aspects typical of streams where flow responds to snow melt, summer drought, and other seasonal events.

The flow record of the Cache River at Patterson, AR was examined using harmonic analysis. This record included partial or complete flow records for the years 1928 through 1931 and 1938 through 1989. In addition to stream gage records, this river and its basin have extensive historic land-use records as well as data gathered by the various remote sensing methods. Flowing through a wetland designated as one of profound importance (Kleiss 1993), studies of its hydrology and landscape ecology are ongoing. Therefore, new analysis techniques have a high potential for validation. Harmonic characteristics of the flow history of the Cache River are illustrated in Figure 2.

- The mean for each month in each time period ("decade") represented by the gage at Patterson, Arkansas, was determined. Because the record from 1921 through 1940 was available for only 12 years, this period was considered a "decade" for the purposes of this study.

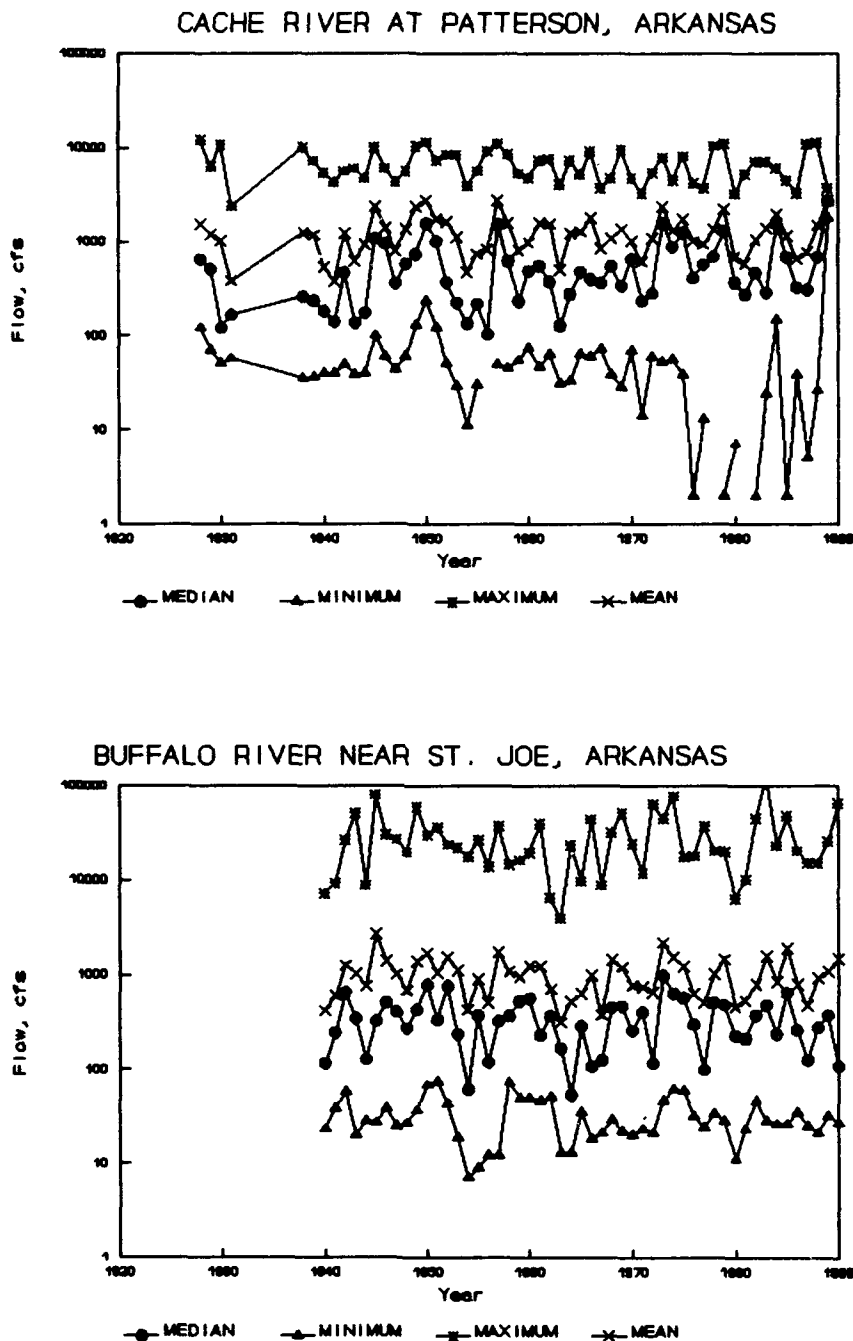


Figure 1. Yearly medians, minima, maxima, and means of selected steamflows in the White River Basin (Arkansas/Missouri). Note that the scale of flow is logarithmic and that recording periods do not include some years

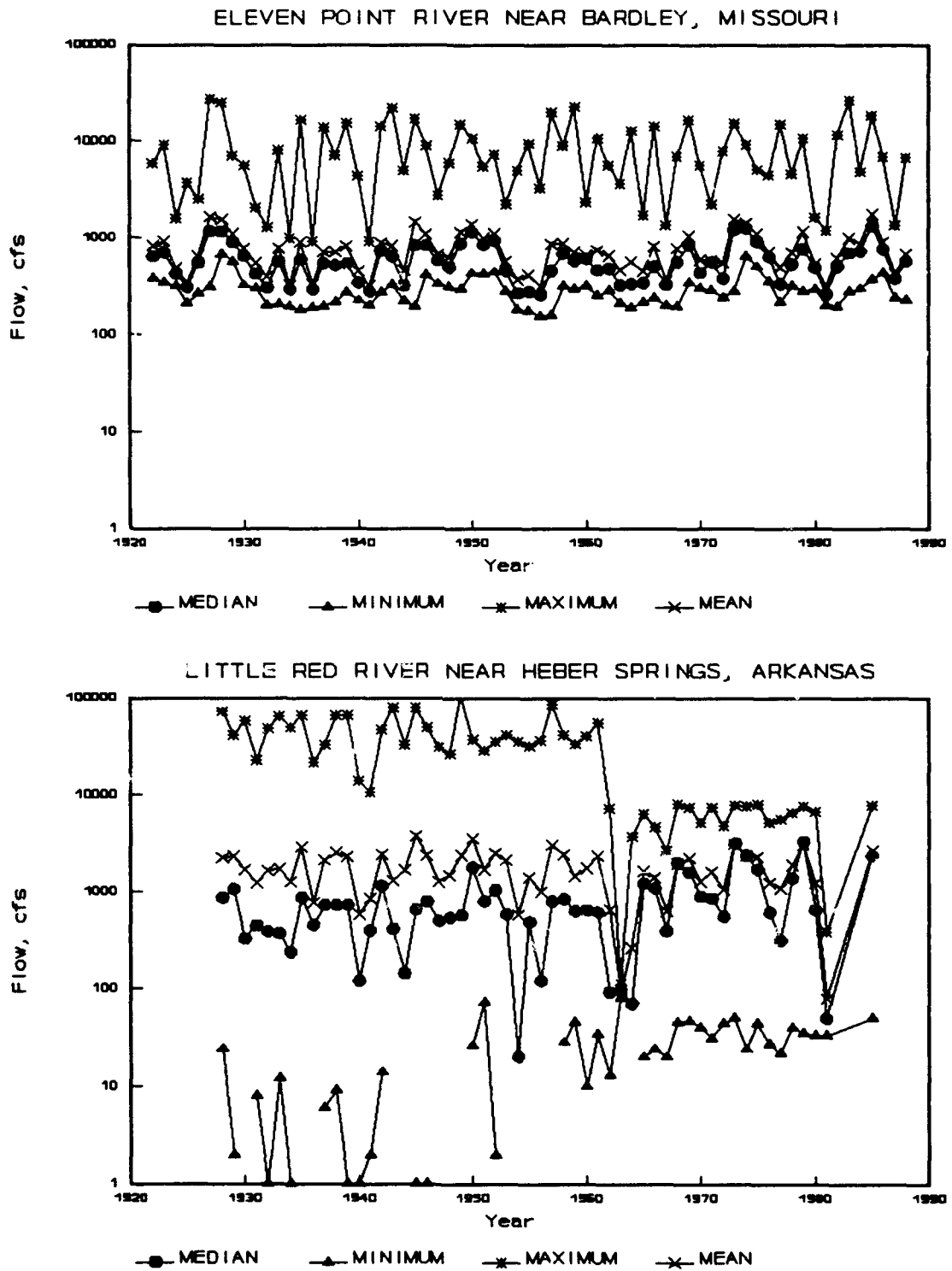


Figure 1. (Concluded)

- Of this resulting set of means, the mean, minimum, and maximum for each month in each decade were determined.
- Cosine curves were fit to the mean, minimum, and maximum values, respectively, for each decade using the PROC NLIN routine (SAS 1988).
- This procedure provided the coefficients (phase, amplitude) with period of one year used to produce the curves in Figures 2 to 5 corresponding to the respective months of the year.

Harmonic analysis also is convenient to compare flow patterns of rivers in the same or nearby watersheds, possibly permitting inference of regional or global effects. Figures 2 to 5 show results of the application of the harmonic analysis technique to the four streams presented in Figure 1. The minimum flow curves for each decade describing the Cache River reveal the progressive changes in both phase and amplitude, being conspicuous in the decade 1961-70. It should be noted that the cosine approximation may not always yield the "best" fit to the data compared to some other model.

In contrast, the harmonic analysis of the daily flow records of the Buffalo River (Fig. 3) reveals no similar deviation from the cosine function, while a corresponding analysis of the Eleven Point River (Fig. 4) shows a fairly consistent relationship between maximum means and means from decade to decade, with a "flatter" curve representing the minimum means in all decades but that of 1951-60. The record of the Little Red River (Fig. 5) reveals extreme fluctuation of the minimum monthly means until the decade of 1961-70, when the minimum curve became quite flat by comparison. These comparisons indicate that one or more fundamental changes occurred in the stream and/or basin either during the time period in question or in prior years (delayed effect) and these warrant further study. This easily observed phenomenon corresponds with the time of complete regulation of the stream to form Greers Ferry Lake, demonstrating the method to be sensitive to at least extreme events.

The ratio of the amplitude (estimated using PROC NLIN) to the corresponding mean (minimum, maximum, or median) of monthly flows for the time period of interest, can be used to summarize the strength of the seasonal pattern ("*seasonality index*," modified from Nestler 1993). Higher values of this ratio indicate stronger seasonality in the flows, whereas lower values indicate unpredictability, or randomness, which is not necessarily dependent on season of the year. Figure 6 shows the Eleven Point River with low values of the index throughout its time period, whereas the values of the indices of the Cache River and the Little Red River generally decline with passing years. The seasonality indices for the maxima, minima, and medians are also shown to permit comparison of these statistics as well. Note that highest seasonality index values were obtained for the minima (compared to the other three statistics considered) for all streams except for the Eleven Point River.

CONCLUSION: Harmonic analysis is one technique for assessing cumulative impacts on wetlands. Streamflow (as well as groundwater) records available in many locales often span many years and may provide insight in definition of present wetlands whose current conditions have been dictated, at least in part, by these historic water conditions. In conjunction with land-use practice histories and remote sensing records of past conditions, these tools can contribute to cumulative impact analysis integral to overall planning, management, and protection of valuable and dwindling wetland resources.

Data provided by EarthInfo, Inc., US Geological Survey, and the US Army Engineer Districts were used in the formulation and validation of the techniques presented.

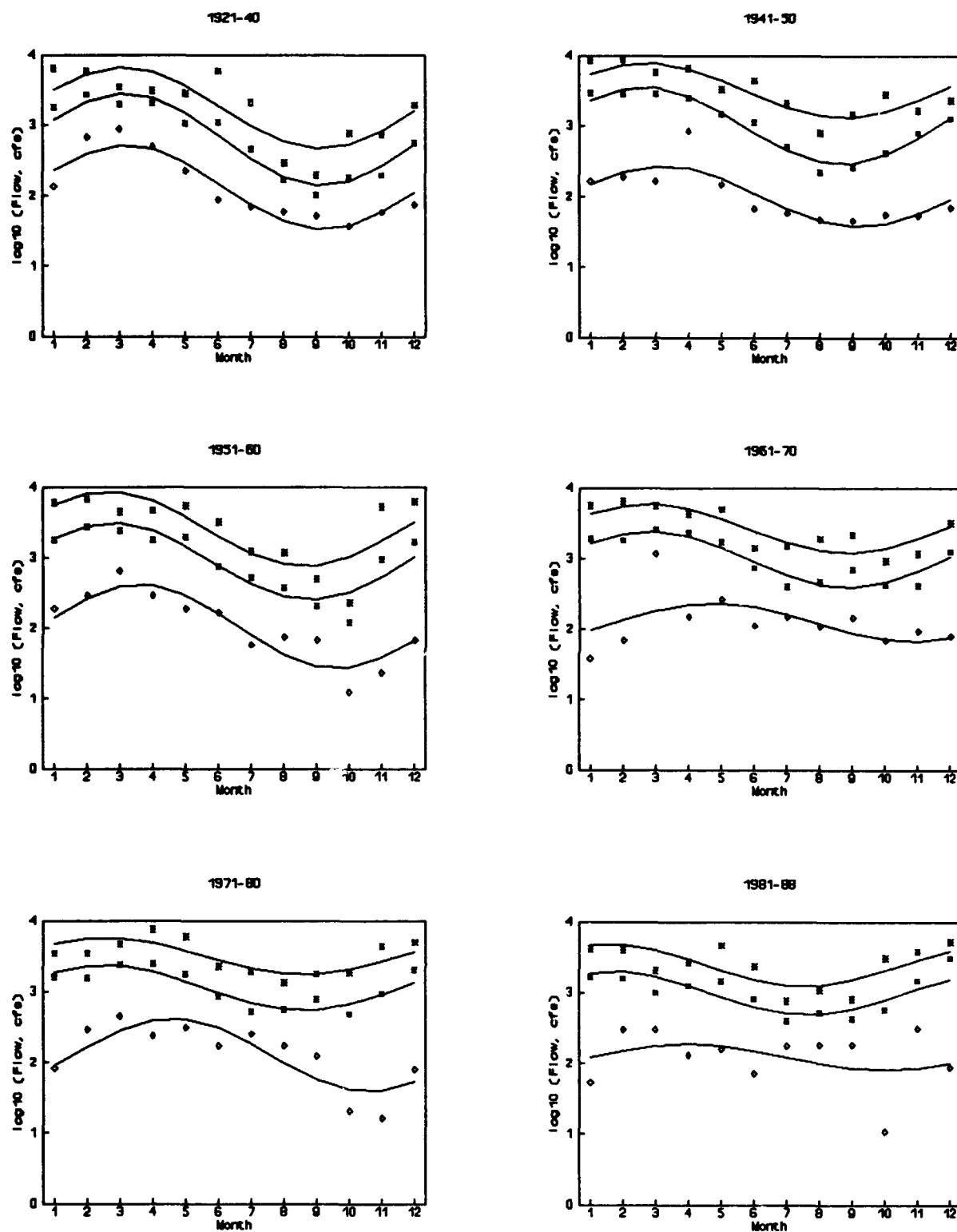


Figure 2. Harmonic analysis of the Cache River at Patterson, Arkansas

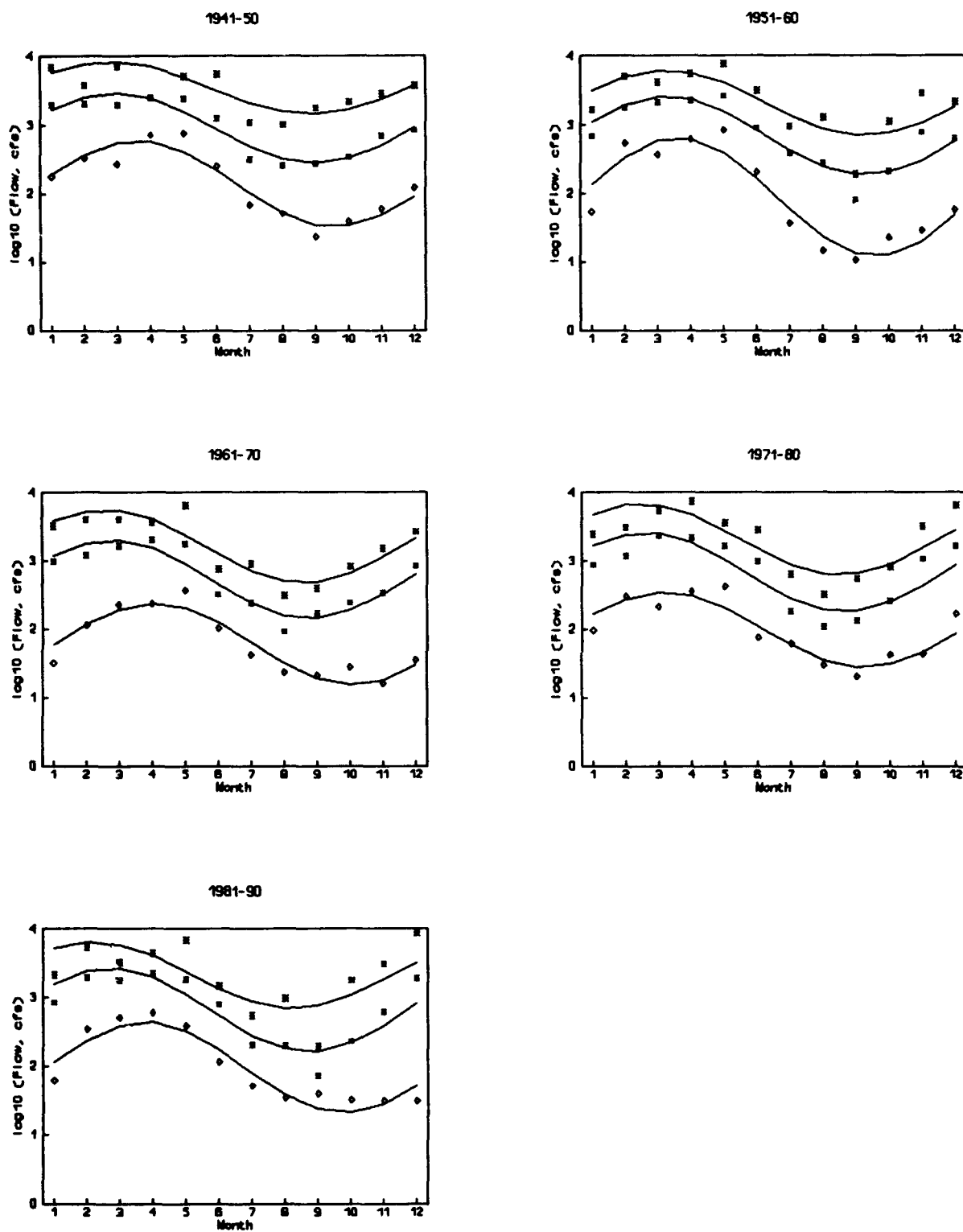


Figure 3. Harmonic analysis of the Buffalo River near St. Joe, Arkansas

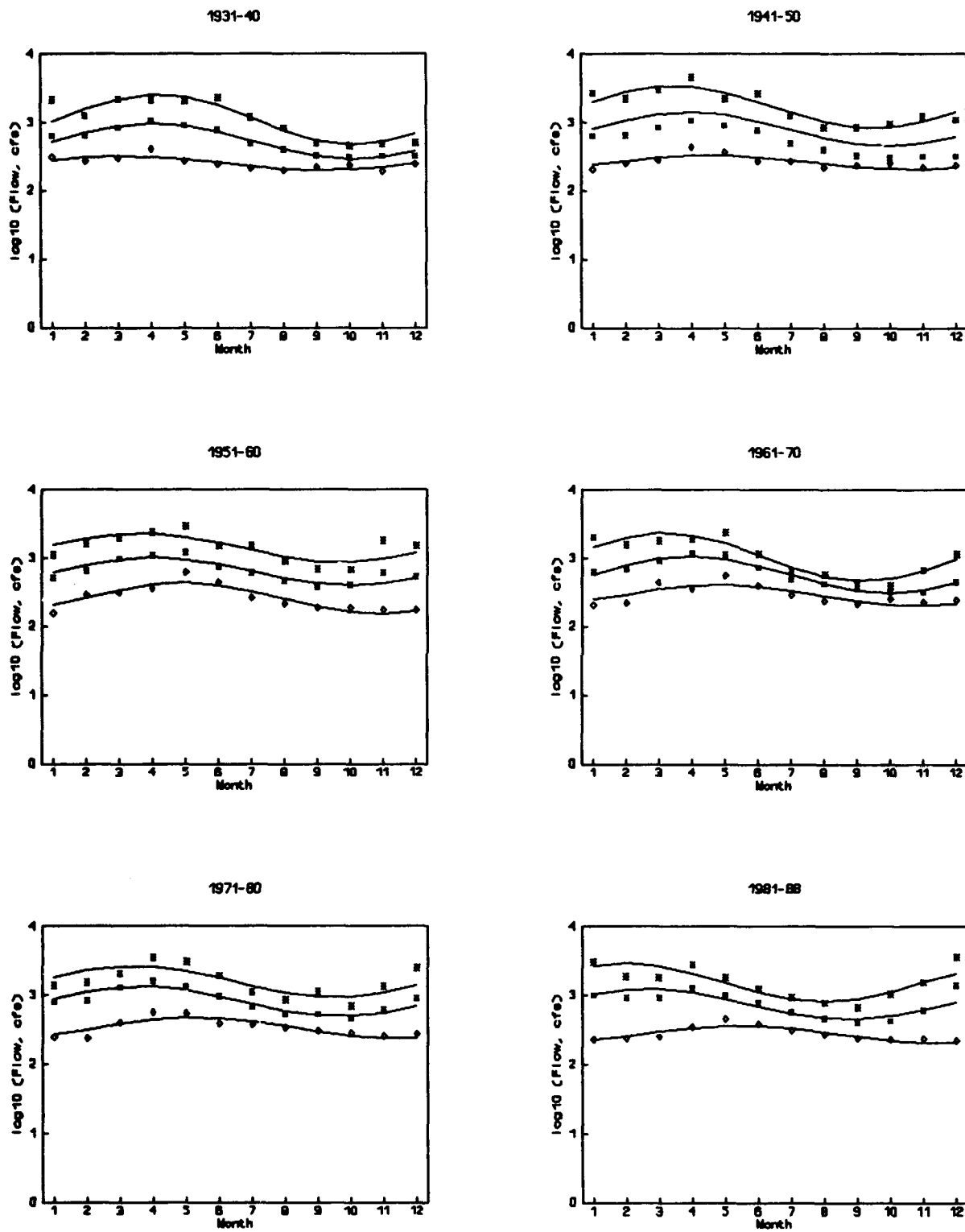


Figure 4. Harmonic analysis of the Eleven Point River near Bardley, Missouri

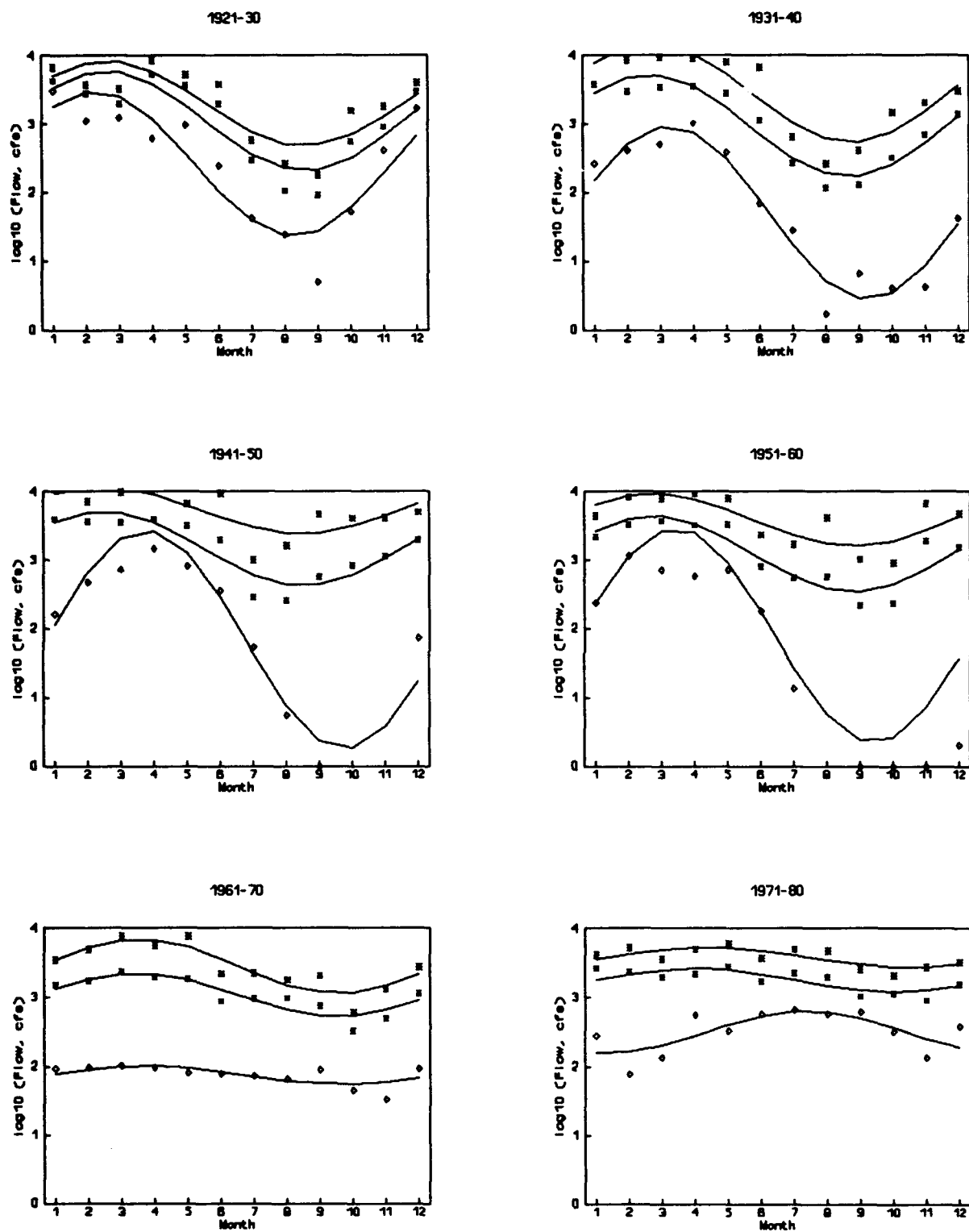


Figure 5. Harmonic analysis of the Little Red River near Heber Springs, Arkansas

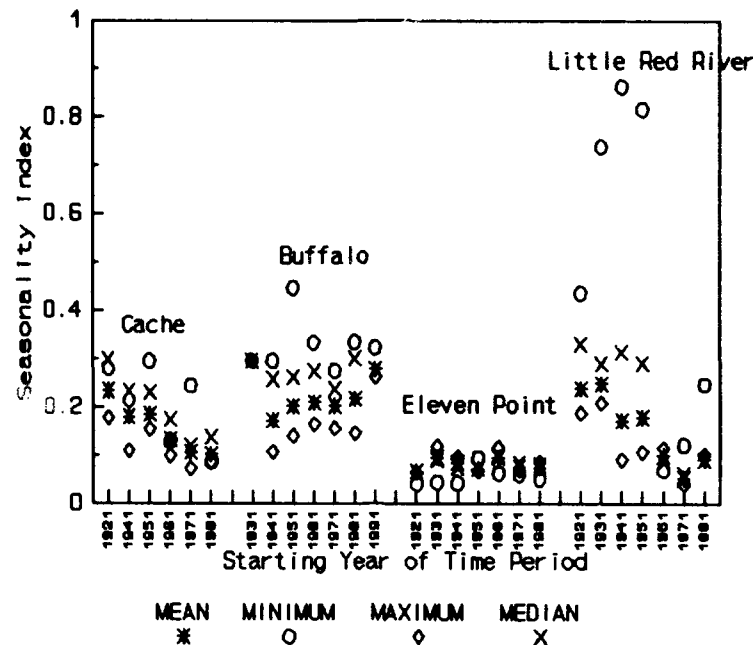


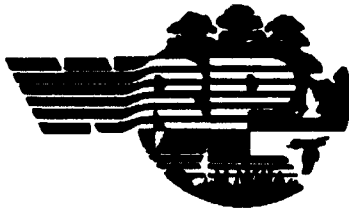
Figure 6. Seasonality indices of means, minima, maxima, and medians compared for four gages in the White River Basin, Arkansas/ Missouri

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- Kleiss, B. A. 1993. "Cache River, Arkansas: studying a bottomland hardwood (BLH) wetland ecosystem." Vol 3, No. 1. The Wetlands Research Program, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Long, K. S. and Nestler, J. M. March 1994. "Assessing cumulative impacts on wetlands: Applying time-scale analysis to hydrologic data," Wetlands Research Program Technical Note HY-IA-2.2.
- Nestler, J. M. 1993. "Instream flow incremental methodology: a synopsis with recommendations for use and suggestions for future research," Technical Report EL-93-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Nestler, J. M. and Long, K. S. 1994. "Framework for cumulative impact analysis of wetlands using hydrologic indices," Technical Report WRP-SM-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- SAS Institute Inc. 1988. "PROC NLIN" (computer program), IBM-PC, SAS Institute Inc., Cary, NC.

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Time Scale Analysis Can Assess Hydrologic Cumulative Impacts

PURPOSE: This note describes an aid for assessing cumulative impacts on wetlands. Certain analysis techniques are employed to reveal time-frames when disruption to basic flow patterns may have occurred. This information is significant when attempting to perform cumulative impact analysis (CIA).

BACKGROUND: Water-level patterns largely determine the nature of wetlands. Therefore, studies of historic water trends associated with wetlands should explain causes-and-effects operating on wetlands and the resulting landscape/ biotic composition. Keys to characterizing historic water-level trends are called "hydrologic indices."

SIMPLE INDICES SAMPLE: Hydrologic indices may be categorized as either simple or complex. Simple indices are easy to compute and include parameters such as mean, median, and range of flows. However, these indices often fail to describe adequately periodicity, seasonal behavior, or evolution of stream character resulting from land-use changes and channelization.

Despite obvious limitations, such simple indices can reveal important features of streamflow and how they compare with those of other streams in the same basin. These simple indices can also give clues regarding the timing of historic, momentous events, such as the abrupt decrease of the monthly maximum flow in the Little Red River record (1961) shown in Figure 1 with records of other selected streams in the White River Basin (Arkansas/Missouri).

The effects of more subtle but perhaps no less profound impacts may be better detected and quantified using indices that are somewhat more complicated to derive but which may yield more insight into cumulative impact analysis. One such index, time-scale analysis, is given here. Another index, harmonic analysis, is treated in WRP Technical Note HY-IA-2.1.

TIME-SCALE ANALYSIS INDEX: Time-scale analysis compares relative "short-term" vs. "long-term" fluctuation in stage/levels of flow. This index relies on the theory of fractals (Peitgen and Richter 1986, Turcotte 1992), specifically that seemingly complex physical patterns such as daily stream flow vary in much the same way in a short period (few days) as in a longer period (many days)—the same shape is found at another place in another size. (The respective time periods are "self-similar").

An important fractal property, the fractal dimension, is commonly obtained using a "method of rulers." In this approach, progressively larger rulers are used to measure the perimeter of physical feature. A straight-line relationship between the common logarithm of both ruler length and perimeter is indicative of strong fractal properties. The slope of this line is termed the "fractal dimension." This relationship implies that a single underlying pattern is being repeated, but at different scales, within the feature.

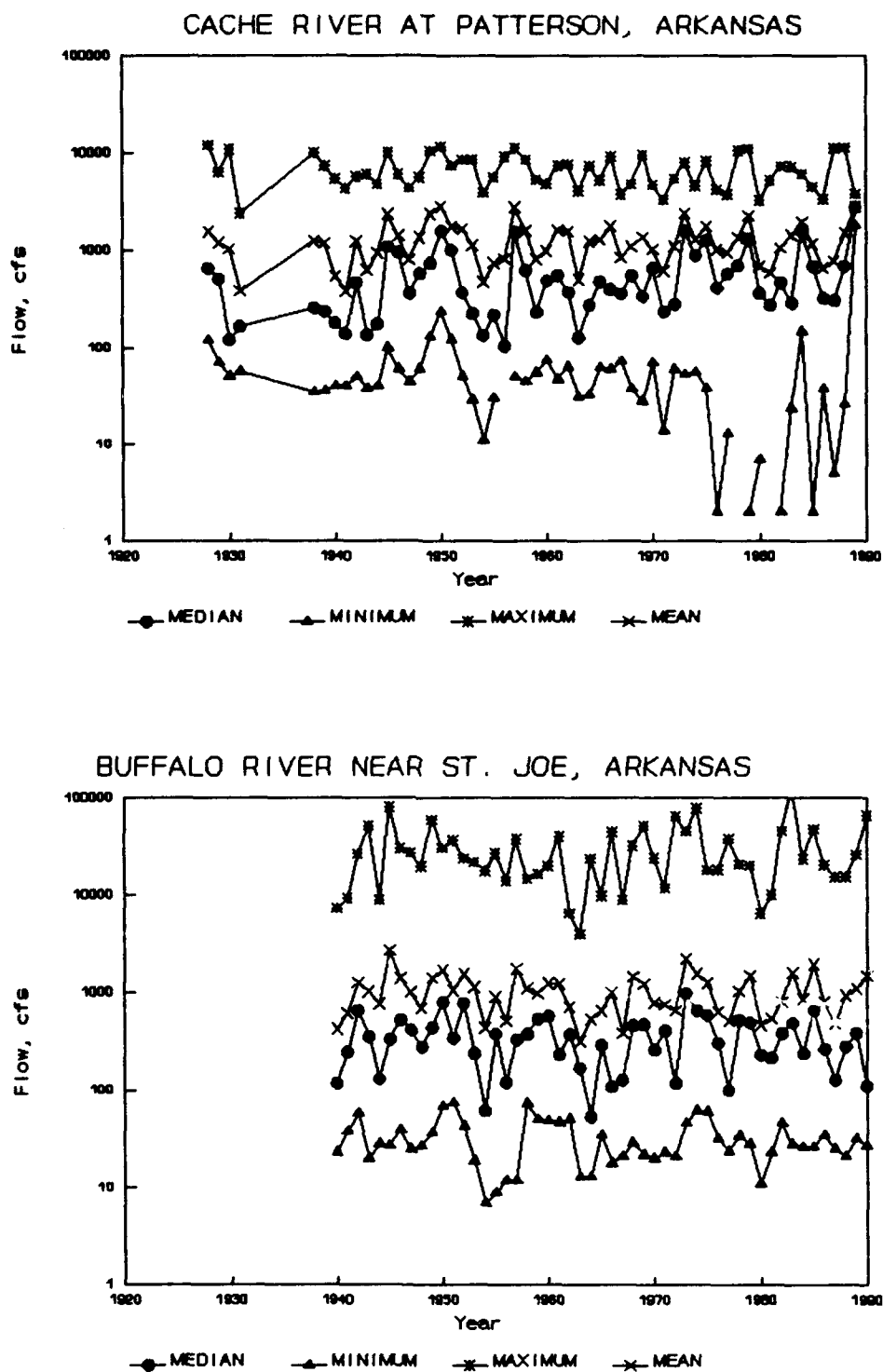


Figure 1. Yearly medians, minima, maxima, and means of selected steam-flows in the White River Basin (Arkansas/Missouri). Note that the scale of flow is logarithmic and that recording periods do not include some years

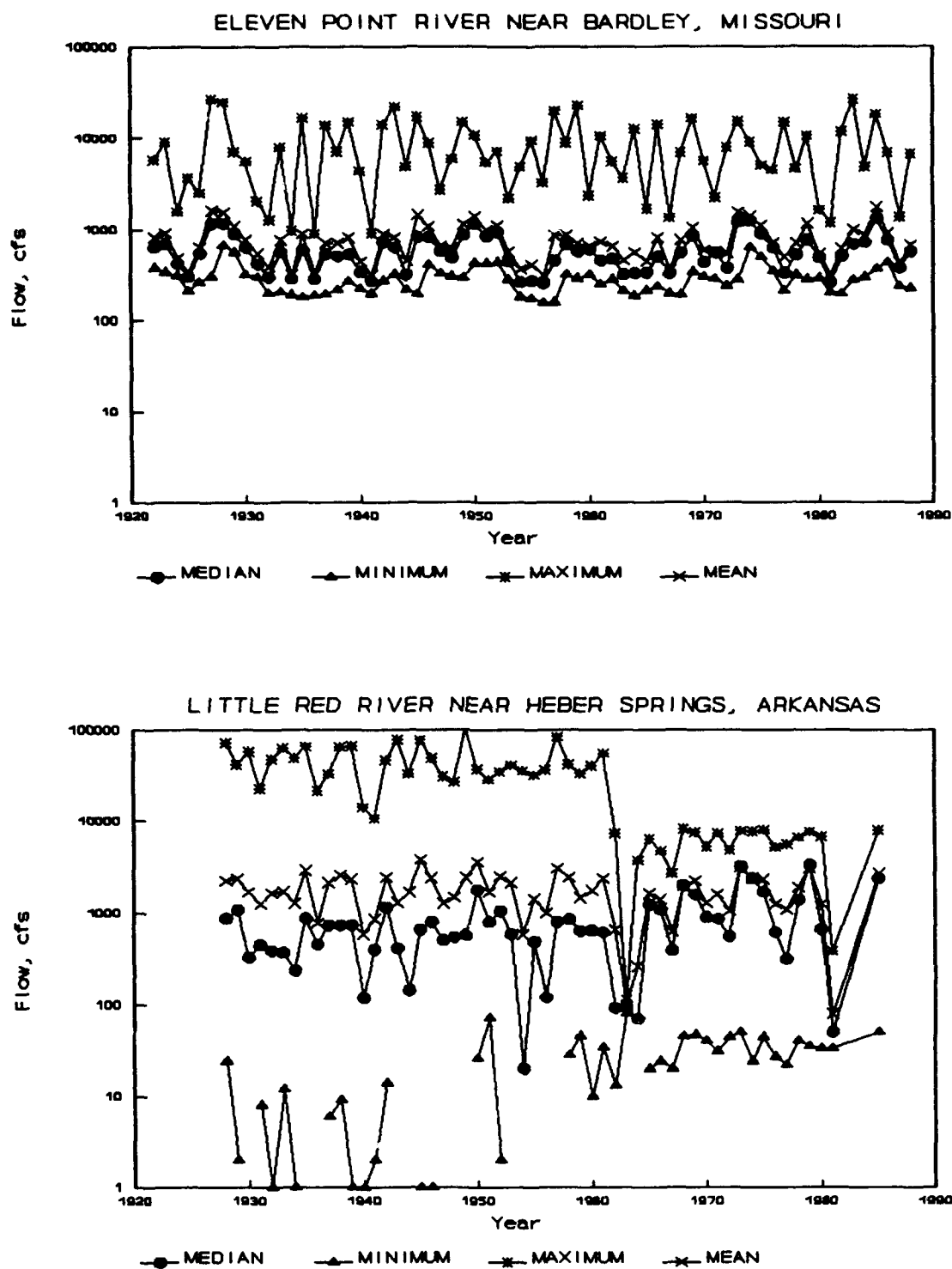


Figure 1. (Concluded)

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Hydrologic time series are known to exhibit fractal properties (Changnon et al. 1991). For the Cache River application, these properties were described using discharge averages, "time dimension," based on different durations instead of rulers of different lengths, "distance dimension." The concept of evaluating information lost as a function of the resolution of measure is similar. Mean monthly flows were calculated for the period of record. Daily flows were then simulated by linear interpolation between adjacent months. The error between the synthesized daily flows based on monthly means (long-term) and the measured daily (short-term) flows represents primarily the contribution of hydrologic processes that occur at a duration greater than one day and less than one month. Examination of these errors between different basins or between different time periods at one site can provide insight into the dynamics of hydrologic processes that operate for a duration of less than one month.

The concept can be expanded to generate synthesized (simulated) daily flows based on many different time durations. The error between each of the synthesized daily flows and the measured daily flows represents the relationship between the different hydrologic processes that blend together to generate a hydrograph. Long-term trends in these errors indicate changes in the relative contribution of different hydrologic processes to the site hydrograph. As part of cumulative impact analysis, this information provides a partial hydrologic explanation for the results obtained using the simple indices and the harmonic analysis.

Complex hydrologic conditions can be quantified by using "root-mean-square error" (RMSE), resulting in measurement units identical to those of the original data, i.e., cubic feet per second (cfs).

Root mean square error (RMSE) calculated as

$$RMSE = \left[\frac{\sum (S_{i+1} - S_i)^2}{NOBS} \right]^{1/2}$$

where

S - (synthesized daily discharge based on successive time scales), and
NOBS - (number of observations)

is used to measure errors between recorded and synthesized daily flows based on different durations. By computing the RMSE of the same period lengths with individual daily flow values over decades, one can often identify the time frame in which some profound event affected flows.

Obvious departures from a prevailing trend can be observed in records of streams that have been impounded. For example, the Little Red River near Heber Springs or the Missouri River at Randall Dam (Fig. 2) had RMSE values that decreased markedly after the impoundment. In contrast, the RMSE of the low flow values (<200 cfs) of the Cache River at Patterson, *increased* considerably in later decades, implying a "flashier" (less damped flow) stream than was the case earlier in the century (Fig. 3). This information could provide an important clue regarding where, when, and what change(s) made the difference.

Behavior of the respective RMSE compared decade by decade for several different streams in a region may denote a localized or a global effect regarding short-term vs. long-term fluctuations in flow (Fig. 2). This tool may also be employed on certain flow levels, such as demonstrated with the

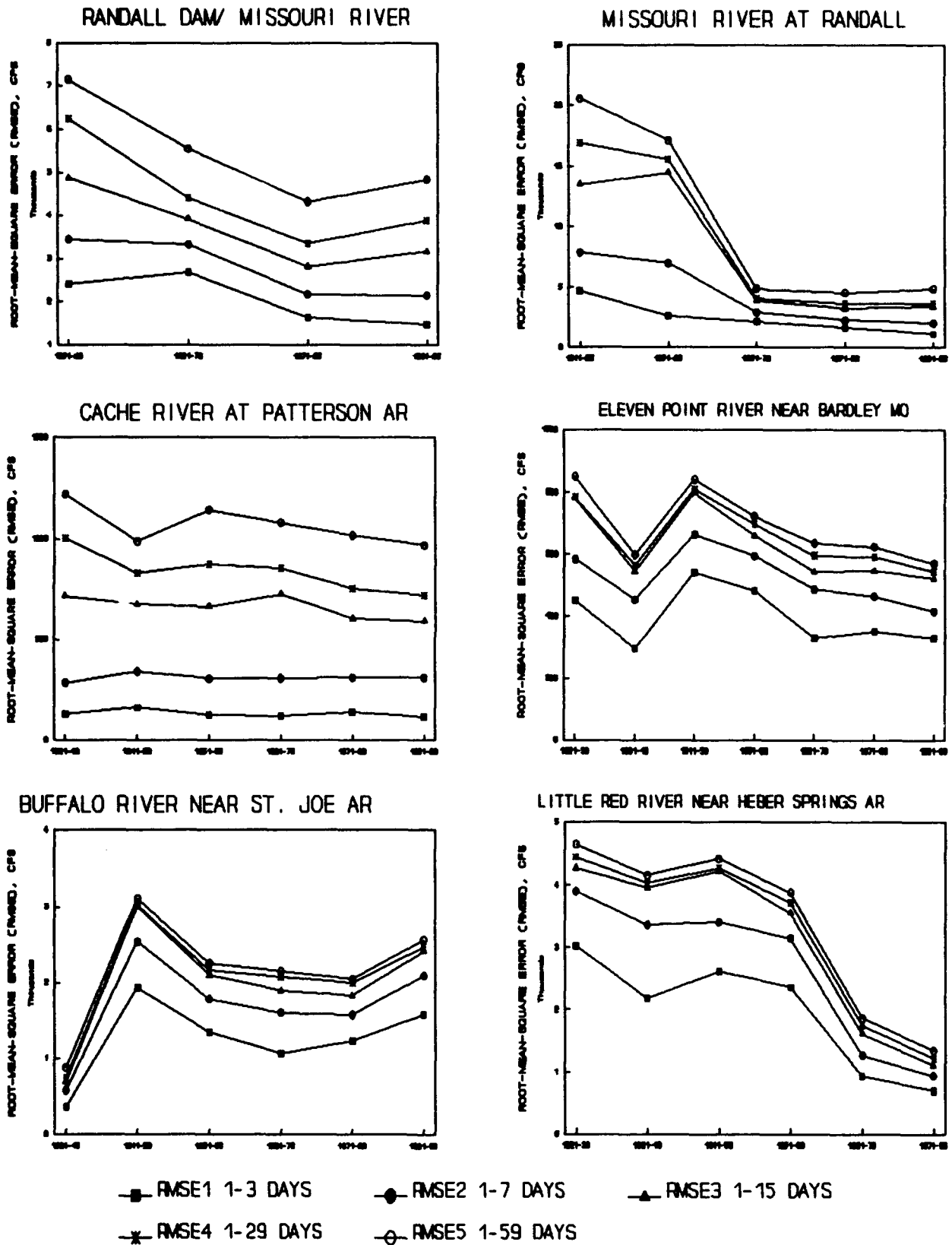


Figure 2. Comparison of respective root-mean-square errors (RMSE) of streams examined with time-scale analysis

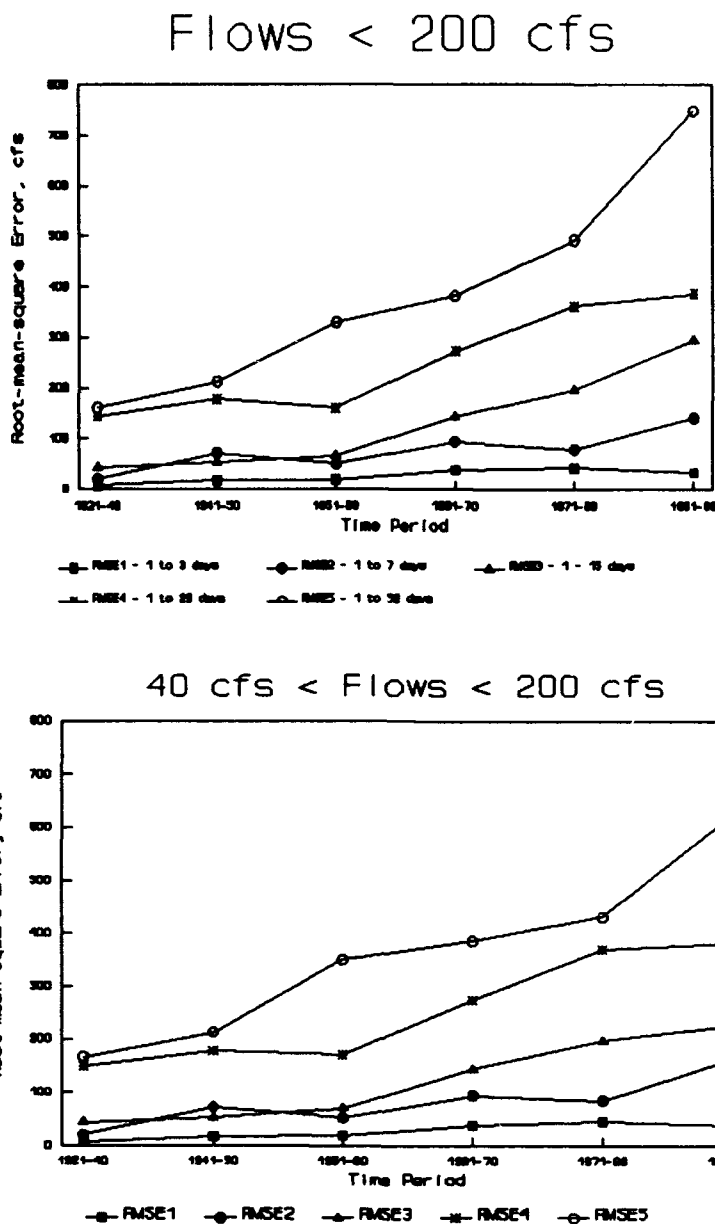


Figure 3. Comparison of root-mean-square error (RMSE) of flows less than 200 cfs of the Cache River at Patterson, Arkansas, with (above) and without (below) flows less than 40 cfs to investigate effects of different recording methods

Cache River flow records (Fig. 3) to explain changes in the lower ranges of flows when level of base flow is of primary interest, e.g., the maintenance of a groundwater level necessary for a particular wetland. No significant changes in the nature of stream flow should yield similar RMSE's for each of the time intervals (days). Additionally, time-scale analyses allow looking at the possible effects of differing recording methods on overall flow analyses. With the recent advent of unattended, automatically recording gages, there might be reason to suppose that more recent measurements might be

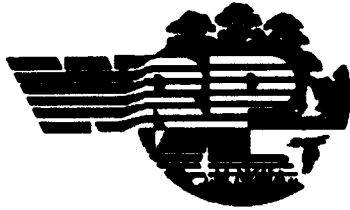
considered more reliable than earlier ones. Upon examining the record of the Cache River at Patterson, it was observed that low flows seemed to be set at a default value of no less than 40 cfs. Hence, one analysis excluded values less than 40 cfs to see if this suspected "artifact" affected overall results. Examining records with errors summarized and compressed such as one may see in Figure 3 reveals only slight deviation in RMSE when recorded values less than or equal 40 cfs were deleted. Thus, even if the values had been estimated, the effect on results was minimal given the expanse of the study of low flows of the Cache River at Patterson, AR. Simple linear regression on the respective RMSEs of the sets with and without lower values, were correlated.

CONCLUSION: Time-scale analysis is a technique offering promise for assessing cumulative impacts on wetlands. Streamflow (as well as groundwater) records available in many locales, often spanning many years, may yield up a treasure of clues defining present wetlands whose current conditions have been dictated, at least in part, by historic water conditions. In conjunction with land-use practice histories and remote sensing records of present and past conditions, these tools can contribute to cumulative impact analysis integral to overall planning, management, and protection of valuable, dwindling wetland resources.

Data provided by EarthInfo, Inc., U.S. Geological Survey, and the U.S. Army Engineer Districts were used in the formulation and validation of the techniques presented.

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Surface Water Sedimentation Processes in Wetlands

PURPOSE: This technical note summarizes the sedimentation processes which control erosion, deposition, and transport of sediment in wetland environments. Related terminology is explained for those lacking specific experience in sedimentation when faced with the evaluation of wetland permits. Future technical notes will cover detailed information on the evaluation of sedimentation in wetlands.

BACKGROUND: Sedimentation in a wetland environment is affected by the hydrology and hydraulics of the wetland and surrounding area. The wetland cannot be isolated from the surrounding environment as erosion and/or deposition on areas outside the wetland may have a profound effect on the sedimentation characteristics within the wetland. The wetland type (i.e. riverine, tidal, depressional, bottomland hardwood, etc.) is also important when evaluating sedimentation. In a riverine bottomland hardwood environment inflowing sediment loads may be transported through the wetland with little deposition. In a depressional wetland all sediment inflow is retained, reducing in wetland size and/or depth.

FACTORS AFFECTING WETLAND SEDIMENTATION: The major factors affecting sedimentation in wetlands include:

- **Inflowing Sediment Load.** The amount of sediment moving into the wetland when considered with the hydraulics determines the location and amount of sedimentation. Generally, the higher the load and the coarser (larger grain sizes) the material, the more deposition will occur in the wetland.
- **Size Distribution of Inflowing Sediment and Wetland Bed Material.** The size distribution (percentages of sands, silts, and clays) will determine where deposition will occur within the wetland. If the sediment sizes are primarily in the sand range, deposition can be expected in and near channels and nearby areas where velocity is reduced. For clay and silt sizes, deposition can be expected throughout the wetland. Erosion will normally occur only in areas of high velocity or high turbulence, usually near outlets or along channels and concentrated flow paths in the wetland.
- **Velocity and Turbulence of Water.** The velocity of the water in the wetland will be the major factor in determining which sediment sizes will be deposited there and where deposition takes place. The amount of turbulence within the flow will have an effect and is correlated with the velocity structure. For erosion, soil type, amount of plant cover, degree of soil compaction, and velocity and turbulence determine the amount and size distribution that will be eroded. The eroded size distribution will be controlled by the bed material of the wetland and the flow velocity.
- **Wave Action.** Waves within a wetland from wind or boat traffic will have an effect on sedimentation. The usual effects are to redistribute sediment that has been deposited by other means and to cause bank failure/erosion due to wave induced forces. Wave erosion can be significant where large areas of open water exist or where boat traffic is uncontrolled.

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- **Wind Erosion and Deposition.** Wind can be a major driving force of either erosion or deposition in wetlands that are dry for portions of the year. Large depressional wetlands in North Dakota have drifts of aeolian sediment up to 3 feet deep in vegetation around the edges of the dry wetlands. Sediment appears to originate from the dry areas in the wetland where there is no cover to prevent wind erosion. Deposition in vegetated areas can also occur when soil is blown from nearby unprotected non-wetland areas.
- **Residence Time.** The amount of time water spends in a wetland will affects the deposition of silts and clays. The longer the residence time, the higher the percentage of sediment that can be settled from the water. If significant turbulence is present in the flow (flow through vegetation for example) fine particles such as silts and clays may not deposit even though residence time in the wetland may be considerable.
- **Density and Type of Vegetation.** The type of vegetation in the wetland, i.e. hardwood trees with little undergrowth or dense cattails or bulrushes, will be important in determining the velocity of flow through the wetland as well as deposition patterns. Studies on a dense growth of bulrushes (*scirpus validus*) indicated that sediment deposited both upstream of and within the bulrush stand. This is apparently due to higher velocities and turbulence within the stand of bulrushes as compared to the relatively still water upstream. The volume of the channel occupied by the bulrushes was about 4 percent of the total volume.

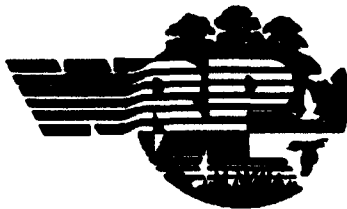
CONCLUSIONS: This technical note reviews important factors in the determination of sedimentation in wetlands. When these factors are used in combination with hydraulic parameters an estimate of expected sedimentation can be made using standard engineering procedures. Several methods are available for estimation of historical, current or future sedimentation such as those discussed in WRP Technical Note SD-CP-4.1 (Jan 93) as well as many computer models.

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Effects of Vegetation on Hydraulic Roughness and Sedimentation in Wetlands

PURPOSE: This technical note summarizes available literature and experimental findings to date on the effect of dense wetland vegetation on sedimentation in wetland environments.

BACKGROUND: Sedimentation processes in wetlands include erosion, deposition, and transport of sediments within and through the boundaries of the wetland. Sedimentation tests conducted on a dense stand of bulrushes (*scirpus validus*) indicate that sediment deposition rates may be lower than anticipated when using average velocities in sediment transport equations.

INTRODUCTION: The calculation of Manning n values has been of interest since the Manning equation was presented in the late 1800s (Henderson, 1966). While estimation of n values for normal channels has been fairly well standardized, the estimation of n values in areas of dense vegetation continues to be subject to large variations depending on the experience of the engineer and the perceived density of the vegetation. Flow resistance and sedimentation in bulrush environments is important in design of constructed wetlands, flood routing through existing wetlands, and determination of flood heights for flood damage studies.

The United States Geological Survey (USGS) published a "Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains" in 1989. This publication indicates that a base n value of from 0.026 to 0.032 should be used for straight uniform channels in firm soil. The guide recommends adding a maximum of 0.100 for "dense cattails growing along channel bottom". Dense cattails and dense bulrushes could be assumed to be similar in hydraulic characteristics. Other adjustments would be for channel irregularity, variation in cross section, and obstructions in the channel. All of the other factors would be zero for the case being tested in this experiment. When using the maximum values from the above range, the n value for a test channel with bulrushes would be 0.132.

EXPERIMENTAL SETUP FOR A WRP STUDY: The facility used to test n values and sedimentation rates in bulrushes consisted of a 1.2 meters wide and approximately 150 meter long concrete lined drainage channel at the Lewisville Aquatic Ecosystem Research Facility in Lewisville, TX (Fig. 1). The channel has 0.67 m high vertical sidewalls with banks above the concrete sloped at about 1V:3H to a height of 3 to 4 m. The test section, approximately 15 m of the drainage channel, was modified by placing a bulkhead at the downstream end of the test section. This allowed the placement of a 0.05×0.15 m stoplog and the retention of approximately 0.15 m of soil on the floor of the channel. The bulkhead was constructed such that the tail water depth could be controlled by the placement of additional 0.05×0.15 m stoplogs. Tests were made for backwater conditions where the downstream water condition was increased by either one or two stoplogs. This increased water depth in the bulrushes by 0.15 or 0.30 m above the level of the soil in the test section.

A weir was placed in the channel 77 meters upstream from the test section to allow free flow at the weir for all flow and backwater conditions (shown in Fig. 2). A triangular weir was used for flows up to 0.044 cubic meters per second, abbreviated as cms in this technical note and a contracted

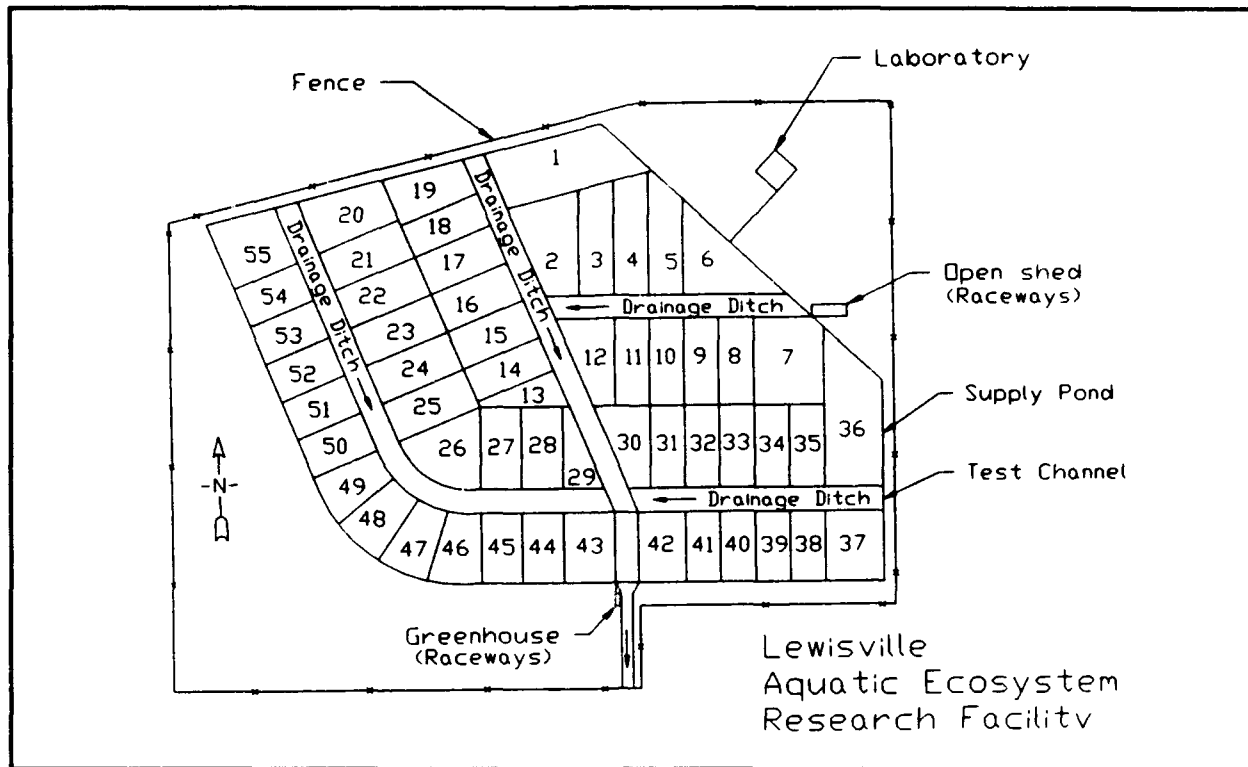


Figure 1. Layout of Aquatic Ecosystem Research Facility in Lewisville, TX showing location of supply pond and test channel

rectangular weir for higher flows. Drainage and/or seepage was present in the channel from ponds located between the weir and the test section. This drainage/seepage flow was measured at the downstream end of the test section prior to each test using a Marsh-McBirney Model 2000 velocity meter. Channel inflow was then adjusted to account for the seepage flow.

Water for the series of tests was obtained from ponds adjacent to the upstream end of the drainage channel. Water was taken primarily from Pond 36 shown in Fig. 1. Pond volume was sufficient to allow a 2 to 3 hour test for each run with a nearly constant flow rate in the test channel. The maximum flow rate that could be obtained using Pond 36 (including channel seepage) was 0.057 cms. A flow of 0.057 cms was sufficient to just overtop the vertical portion of the channel for the high back-water condition. Tests to determine Manning's n values and sediment retention rates were run at flow rates of 0.009 cms, 0.026 cms, 0.044 cms, and 0.057 cms including seepage from the surrounding ponds.

Soft stem bulrushes (*Scirpus validus*) were planted in late April 1992 in soil placed in the bottom of the concrete channel and retained in place by a stoplog at the downstream end of the test section. The bulrushes were allowed to grow from late April until late July 1992. The bulrushes had a continuous supply of water due to seepage and releases from nearby ponds used in ecosystem research. After the test to determine Manning's n values in July 1992, bulrush samples were taken and analyzed for stem count, stem diameter, and dry weight of the plants. The sampled area consisted of nine sample sections each 40.5 cm by 82.3 cm.

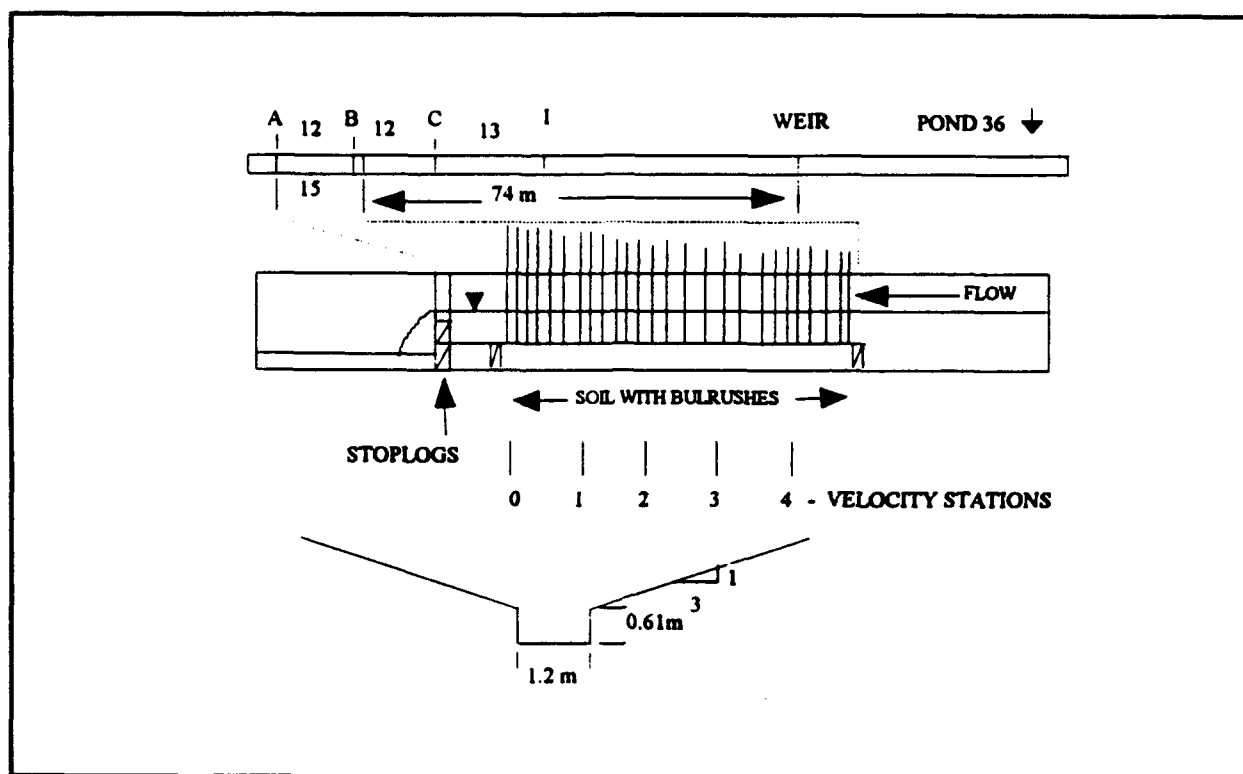


Figure 2. Schematic View of the Lewisville Aquatic Ecosystem Research Facility Test Channel showing test set up and sampling/measurement locations

The planted area was then allowed to continue growing from July until late November 1992 when additional tests were run to determine the ability of the bulrushes to trap fine sediments. The areas sampled after the July tests were not populated as densely as the unsampled area but were located at the extreme lower end of the test section and did not affect the flow except at the extreme downstream end of the test section.

Sediment Testing Apparatus: In late November 1992 the bulrushes were tested for sediment trapping efficiency by introducing a fine grained sediment into the flow upstream of the bulrushes. The sediment consisted almost exclusively of silts and clays with very little sand. Sediment used in the tests consisted of a loessial soil from the Vicksburg, MS area that was transported to Lewisville for the tests. The use of the Mississippi soil allowed easy visual identification of areas where deposition had occurred due to the difference in color between the nearly black soil at Lewisville and the light brown soil from Vicksburg. Approximately 150 liters of sediment material was transported and proved to be adequate for the series of tests.

The experimental setup for the analysis of fine sedimentation in the bulrushes consisted of a mixing tank for mixing a sediment slurry, a pump for injecting the slurry into the channel, and turbulence producing devices (cinder blocks) which were placed in the channel to create turbulence and speed sediment mixing. Sediment deposition was indirectly measured by sampling sediment concentrations at three points in the test channel using a standard DH-81 suspended sediment sampler. The test points (labeled A, B, and C) are shown in Figure 2 as well as the location of the sediment injection apparatus (I). The sediment samples were then analyzed for sediment concentration and a grain size analysis was performed using an Elzone model 112 LSD particle size analyzer.

EXPERIMENTAL RESULTS:

- **Bulrush Growth and Density.** The bulrush stand as tested for the Manning's n value determinations was well established in late July with an average of 403 stems per square meter. The average diameter for the bottom 50 cm of the stems was 0.7 cm and the volume of stems in the lower 50 cm of water was $8,704 \text{ cm}^3/\text{m}^2$ or 1.7 percent of the total channel volume. Sedimentation testing was performed 4 months after the initial Manning's n value testing. By the November test date, plant densities had doubled from an average $402 \text{ stems}/\text{m}^2$ to $807 \text{ stems}/\text{m}^2$. Stem diameter had also increased from 0.70 cm to 0.76 cm. The bulrushes occupied an average of 4.0 percent of the channel volume in November compared with 1.7 percent in July. Plant dry matter content (for the entire plants) had increased from 442 grams per square meter in July to 1502 grams per square meter in November.
- **Manning's n Value Determination.** The water surface profile was measured for each test flow rate for two different tailwater conditions. The first condition tested in July was with one additional stoplog in place (total stoplogs equal to 2 - one to retain soil and second to raise tail water above channel bed). This condition is noted as the low tailwater condition in the following tables and discussions. The second condition for the July tests used two stoplogs in addition to the base stoplog and is referred to as the high tailwater condition. Water surface elevations and velocity measurements were taken at five stations along the test section. The stations are shown in Fig. 2 and are located at the upstream and downstream ends of the section and at every 3 meters along the test channel between the ends of the bulrushes (labeled as 0 to 4 on Fig. 2). One set of water surface profile measurements was also taken for the November sedimentation tests for a flow rate of 0.044 cms. During the remaining November tests only the water surface elevation values at the upstream and downstream end of the test channel were recorded, but the water surface slope was relatively constant along the channel for the high tailwater cases during July testing.

The results of the five cross sectional velocity and depth values obtained in the July tests were averaged for each flow rate and the averages are presented in Table 1. Tests listed under "Observed" columns are the velocity values measured in the channel using a Marsh-McBirney Model 2000 velocity meter. The velocity measurements were taken at a standard 20-, 60-, and 80-percent depth measured from the water surface. Values used in these calculations are the 60 percent observations. Velocity values shown under "Calculated" headings were obtained using the flow rate divided by the wetted area to obtain an average velocity. It can be seen that there is a wide scatter in the computed Manning's n values for these tests. The n value varies from a low of 0.164 to a high of 0.929. The differences between using the observed and calculated velocity values also show wide variation in n values with differences of 1.1 percent to 149.7 percent. It should be noted that the calculation of n values normally uses the average velocity for the cross section and not point measurement values. This indicates possible problems in measuring velocities in bulrush flow areas and calculating flow rates by multiplying measured velocities by measured cross sectional areas.

The calculated values show a definite trend towards reduction in n value with increasing velocity as shown in Figure 3. This decrease cannot be construed as a result of bending of the bulrush stems since all velocities are well below threshold velocity where the stems would begin to bend. The November tests with double the number of bulrush stems show a similar trend at a significantly higher range. The difference in n value as a result of using the calculated average velocity versus an average of observed velocities can also be seen in Figure 3. At the very low velocities, the accuracy of the velocity meter and the inability to measure slope extremely accurately may account for much of the difference between observed and calculated values.

Table 1. Manning's n Values for Soft Stem Bulrushes.

July 1992 Test							
Flow	Tail-water	Slope m/m or ft/ft	Observed Velocity (Average) mps (fps)	Calculated Velocity (Q/A) mps (fps)	Obs n	Calc ^a n	% n Diff O-C C
0.009	low	.0088	0.067 (0.22)	0.073 (.24)	.297	.261	13.8
	high	.0010	0.015 (0.05)	0.024 (.08)	.929	.372	149.7
0.026	low	.0105	0.107 (0.35)	0.101 (.33)	.423	.291	45.4
	high	.0035	0.073 (0.24)	0.064 (.21)	.329	.339	-2.9
0.044	low	.0145	0.152 ^b (0.50)	0.137 (.45)	.180	.271	-33.6
	high	.0040	0.095 (0.31)	0.091 (.30)	.262	.265	-1.1
0.057	low	.0145	0.180 (0.59)	0.155 (.51)	.164	.254	-35.4
	high	.0050	0.293 (0.96)	0.110 (.36)	.178	.282	-36.9
Average					.345	.292	18.3
November 1992 Test							
0.010	high	0.0028		0.024 (0.08)		.697	
0.026	high	0.0085		0.058 (0.19)		.585	
0.044	high	0.0120	0.119 ^c (0.39)	0.088 (0.29)	.367	.501	
0.064 ^d	high	0.0198		0.119 (0.39)		.497	
^a Using calculated velocity (Q/A). ^b Velocity value of 0.54 (1.77) not included. ^c Only test where velocities were measured during November testing. ^d Flow is higher due to seepage from rainfall just previous to test.							

When the November test began it was found that the upstream 3 m were filled with debris, trash, and moss that had been washed down the channel. This debris had caused some of the upstream bulrushes to bend downstream and created a large head loss in the upstream portion of the test section. For this reason the first 3 m of bulrushes were removed from the channel and the sediment and n value tests were performed with only 12 m of bulrushes.

The effect of bulrush density can be seen in Fig. 4 where the n value for a condition with no bulrushes in the channel has been estimated using Henderson (1966). The n value for the channel without bulrushes was estimated to be 0.03 (0.32 from USGS 1989). The data indicates that the increase in n value with increasing plant density is nearly linear for the range tested. The ratio of this increase in n averaged 182 percent for a doubling in plant density from 403 to 807 stems per square meter. The factor by which the n value increased due to the increase in plant density was rather stable varying from 1.76 to 1.89 and showing no pattern with regards to increasing velocity.

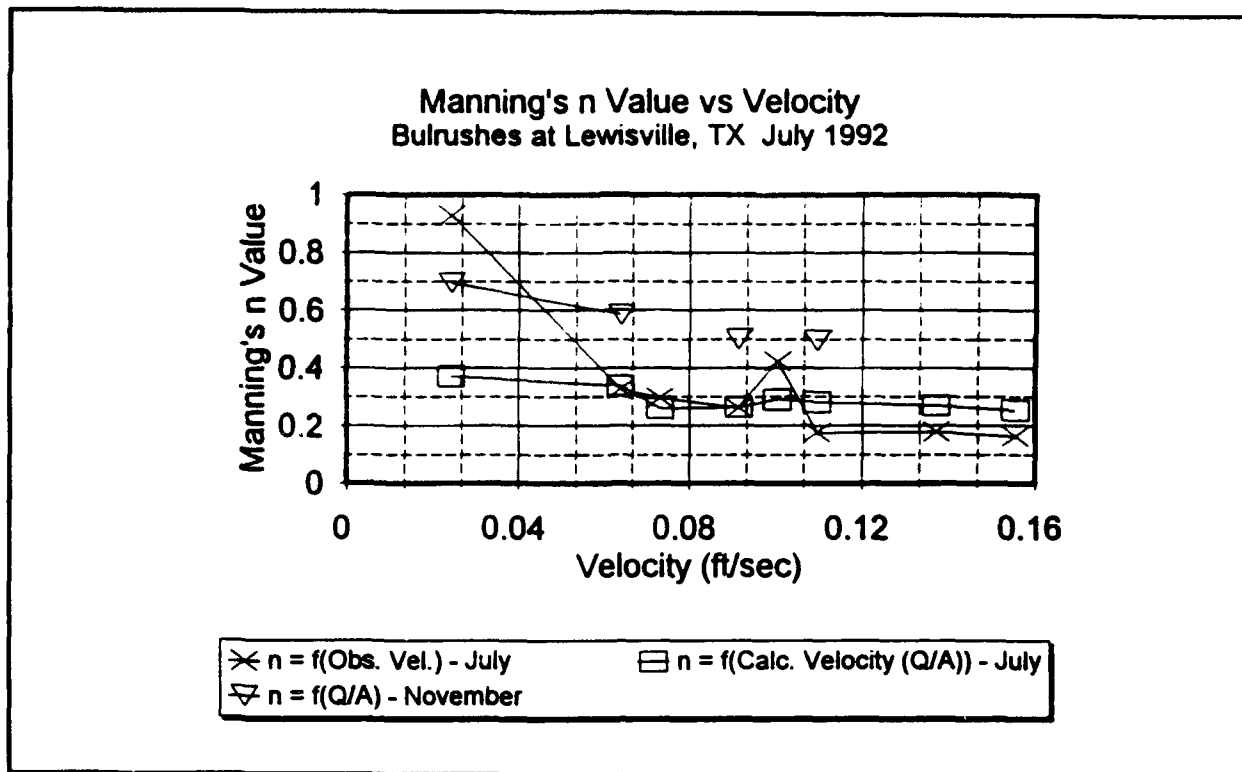


Figure 3. Manning's n Value Versus Velocity for Bulrushes

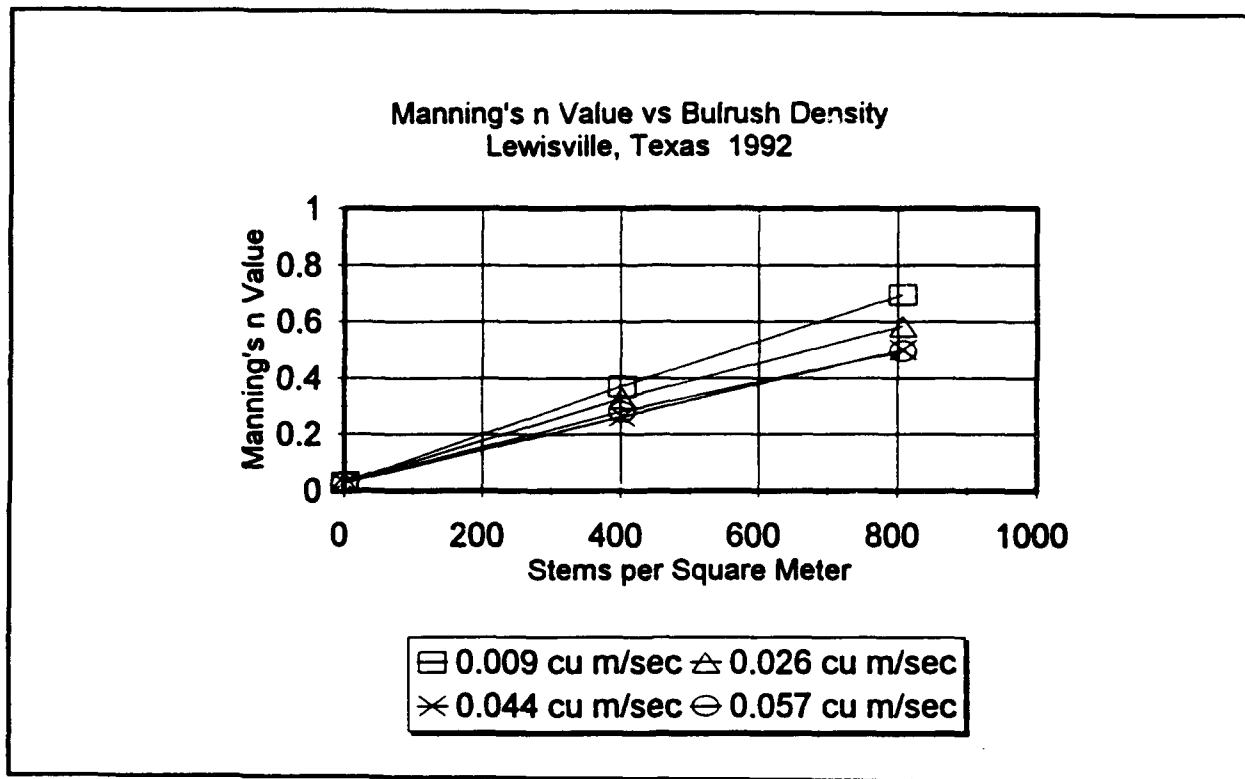


Figure 4. Manning's n Value Versus Bulrushes Density

It was thought that perhaps a change in the coefficient of drag (C_d) could be responsible for the change in Manning's n values due to changing Reynolds numbers or due to the reduction of C_d with increasing Reynolds number. Accordingly, Reynolds number for the various flows were calculated. Stem Reynolds numbers ($Re = \rho * Vel * Dia / \mu$) range from a low of 661 for the 0.009 flow rate in July to a high of 3171 for the 0.0064 flow in the November test. These Reynolds numbers are in the range of a laminar boundary layer and are significantly below the range of the transition to a turbulent boundary layer for flow around a single cylinder. The Reynolds number is high enough to indicate a turbulent wake behind a single cylinder (Schlichting, 1979). These Reynolds numbers are all at a very stable point on the Reynolds number vs coefficient of drag (C_d) curve and the range of Reynolds numbers encountered in this study produce a constant value for C_d . This indicates that the drag coefficient would not account for the variation in Manning's n value when velocities were varied. This was also true when n was compared to velocity multiplied by the hydraulic radius of the channel.

It may be that the reduction in n values with increasing velocity has to do with the effect of turbulence from upstream bulrush stems on flow around the downstream bulrush stems. This effect may reduce flow resistance by causing early transition to a turbulent boundary layer at the downstream bulrush stem or perhaps a cycling between laminar and turbulent, thus reducing drag from the stems and lowering flow resistance.

- Sedimentation. Sediment for the test was introduced 25 m upstream from the channel section where the bulrushes were growing. With the introduction of turbulence at the injection point, 25 m of flow allowed adequate time for mixing of the sediment and water prior to the first sampling point. The first sampling point was located 12 m upstream from the bulrushes.

Based on the desired concentrations of 250 to 500 mg/liter and the desired test flows, sediment was mixed with 460 liters of water to create a slurry in the mixing tank. This slurry was continuously stirred to prevent settling of the sediment. This proved to be extremely important for the higher flow rates when sediment content of the slurry was very high. For the initial test $Q=0.010$ cms a propeller mixer was used to agitate the sediment slurry. This proved to be very difficult and resulted in an increasing concentration with time as shown in Figure 5. For the second test $Q=0.026$ cms the propeller mixer was also used for the initial portion of the test. About a third of the way into the test the mixer quit and agitation was accomplished using a shovel. This method was used for the remainder of the tests and resulted in high concentrations for the end of the 0.026 cms test and rather variable inflow concentrations for the 0.044 cms test. For the 0.057 cms test the results were less variable. A partial analysis was done on a sample of the soil and is shown in Fig. 6 and labeled as SOIL ANAL.

The sediment concentration was sampled at point C, 12 m upstream from bulrushes, point B (before bulrushes), and point A (after bulrushes). Results for the four tests are shown in Figure 6. The sediment concentrations drop noticeably between points C and B while dropping only slightly between points B and A. Two of the tests were also run for approximately the last 20 minutes of the test at a concentration of approximately double that of the previous portion of the test. Results of these partial tests are also shown in Figure 7 at the end of the tests for flows of 0.026 and 0.057 cms.

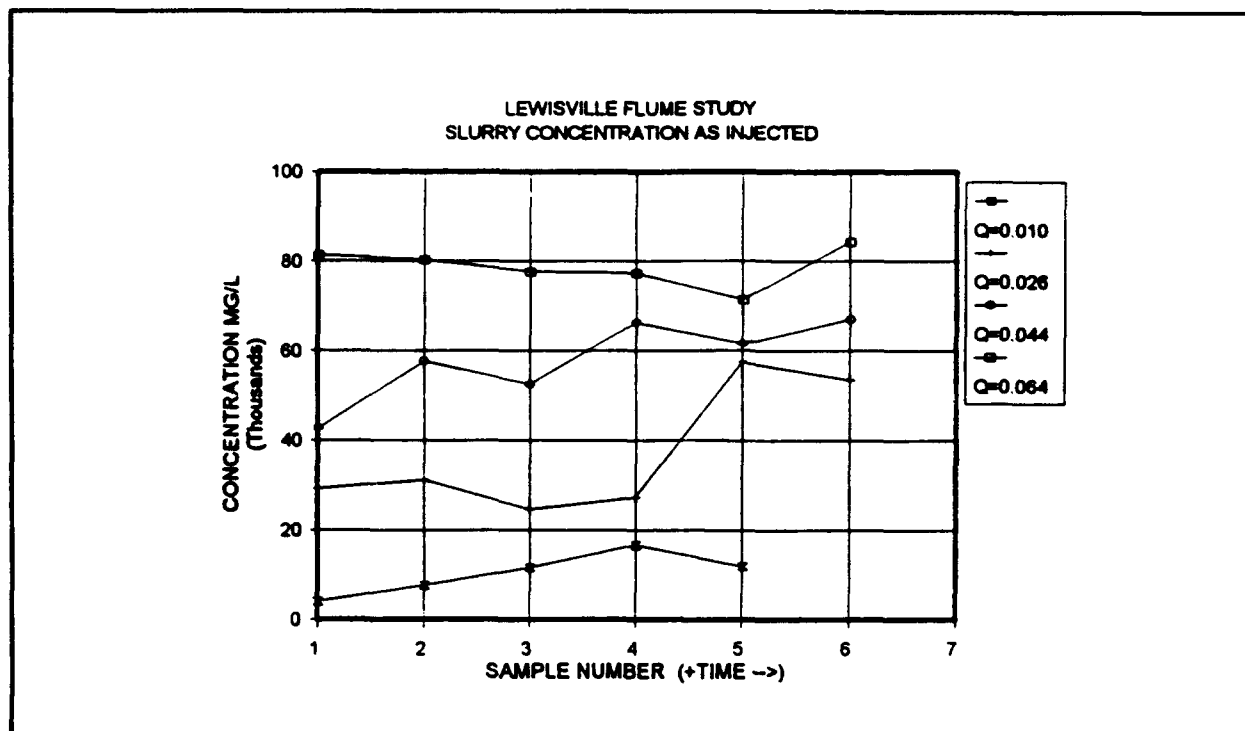


Figure 5. Sediment Concentration of Injected Sediment Slurry

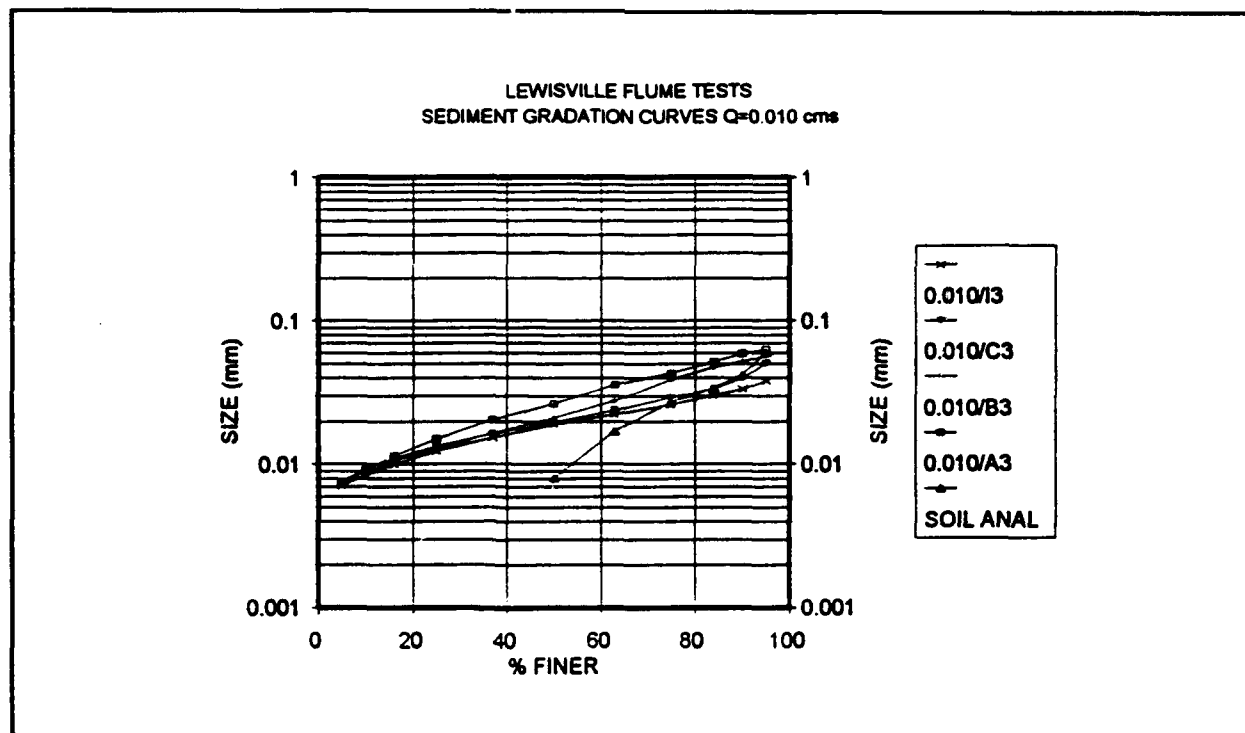


Figure 6. Particle Gradation for Original Soil, Injected Sediment (I), and Collected Sediment Samples (A-C) for Sample Series 3 for Q = 0.010 cms

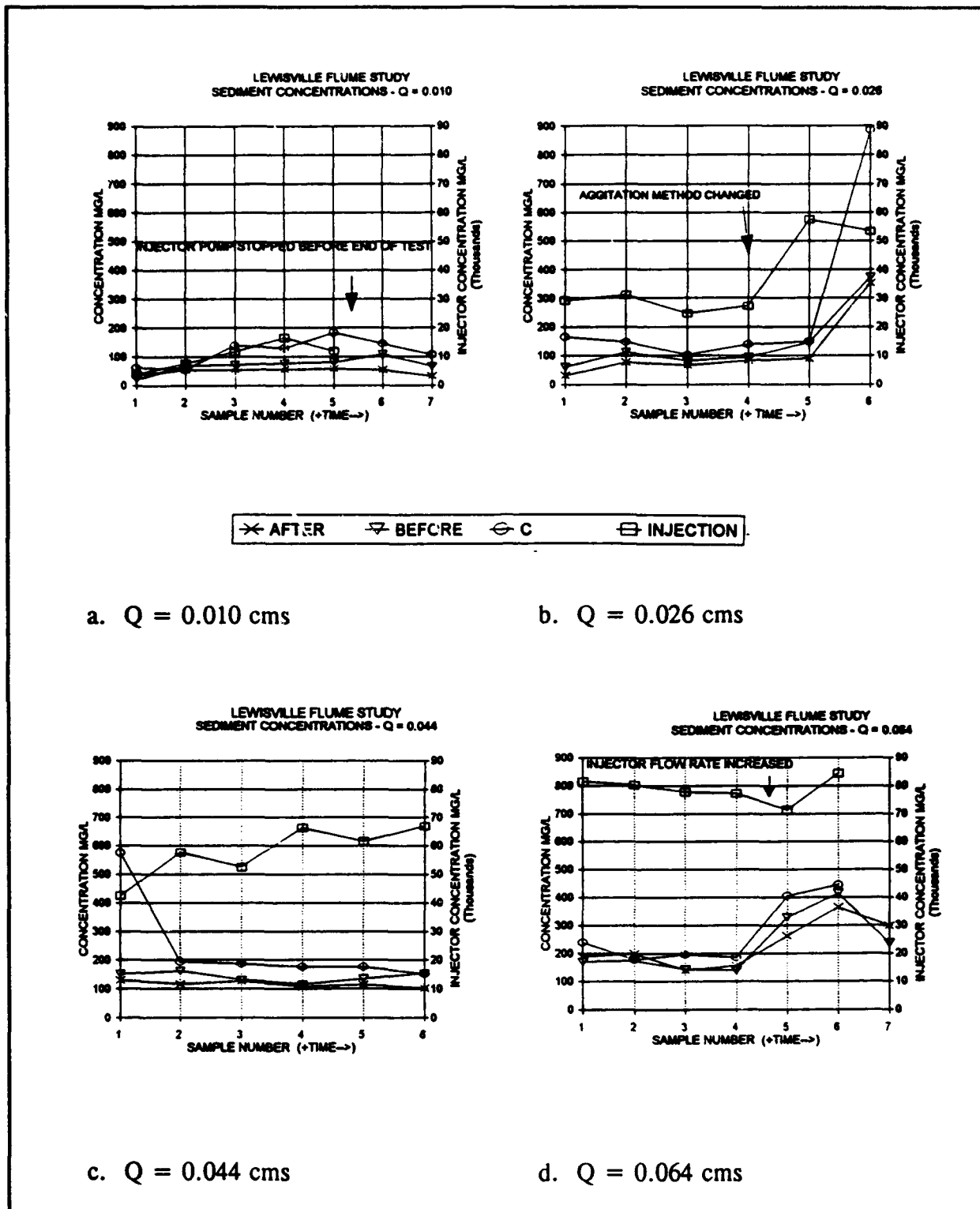


Figure 7. Sediment concentrations for flows of 0.010, 0.026, 0.044, and 0.064 cubic meters per second at sampled locations

Grain size analyses overall showed no significant difference between the injected size distribution and that observed at downstream points, although some tests showed a small trend of grain size fining in the downstream direction. The major difference was a loss of particles at the coarsest end of the distribution. Some differences are noticeable between the soil sample and the collected samples in the 50 percent range and no explanation is available for this difference other than a uncharacteristic sample or possibly a coagulation of clay particles when in contact with the water at the test site. Analysis of the sediment data is continuing.

CONCLUSIONS: Manning's n values were found to be from 2 to 5.4 times as high as indicated by USGS (1989). The n values were found to vary from 0.27 to 0.70 for bulrushes in two differing growth states and with varying flow rates. The n value was found to decrease with increasing velocity for both growth conditions tested for the velocities and flow rates tested. Variations in n value could not be accounted for by changes in the drag coefficient C_d .

Sediment was observed to deposit in the bulrushes but not to the extent that deposition occurred upstream. From this data it appears that less sediment will be retained by bulrush stands than would be predicted due to increased turbulence in the flow in the bulrushes. This increased turbulence and associated maximum velocities is much higher than would be predicted by simply reducing the cross sectional area by the volume of the bulrush stems.

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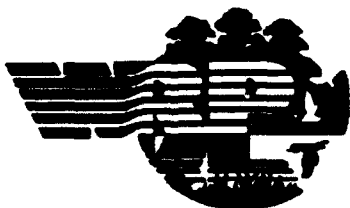
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Predictive Techniques: Wetland Sedimentation Due to Surface Water Flow

PURPOSE: This Technical Note presents conditions for which existing sedimentation technology can be used in wetland areas. Although the term sedimentation embodies the processes of erosion, entrainment, transportation, deposition, and compaction of sediment, this technical note addresses waterborne sediments.

BACKGROUND: Sedimentation processes should be grouped into the broad categories of "local" and "general" processes. Local processes are those occurring over a relatively small space resulting in driving mechanisms that are highly three dimensional in space and dynamic in time. General sedimentation processes are those occurring over relatively large-scale space resulting in driving mechanisms, and response of sediment particles, that can be adequately predicted using one-dimensional dynamic or analytic steady state equations. General sedimentation processes will be discussed below.

SEDIMENTATION PROCESSES: Sediment investigations to date have focused on inorganic material. Particle size has been the key parameter in classifying sediment behavior. The Subcommittee on Sediment Terminology of the American Geophysical Union proposed the classification system in use today (Lane, 1947).

Particle Size, mm	Classification
< 0.004	Clay
0.004 to 0.0625	Silt
0.0625 to 2.0	Sand
2.0 to 64.0	Gravel
64.0 to 256.0	Cobbles
> 256.0	Boulders

Because the behavior of sediment particles is so sensitive to their size, Lane partitioned these broad ranges into class intervals using a geometric progression of 2.

The emphasis in existing reservoir sedimentation studies was on volume depletion in the reservoir pool. Research attention was focused on the deposition and compaction processes involving the finer sediment particles characterized as sand, silt, and clay. Hydrodynamic forces systematically decreased as flow entered the reservoir and once deposited, sediments remained immobile.

In riverine sedimentation, however, the historical research interest has included the processes of erosion, entrainment, transportation, and deposition. The research emphasis has focused on sand and gravel size particles because the forces in riverine systems do not permit the finer silt- and clay-sized particles to deposit.

Estuarine sedimentation studies require a more complete treatment of the problem since the hydrodynamics are complicated by both baroclinic (buoyancy) forces and barotropic (other) forces.

WETLAND SEDIMENTATION PROCESSES: In wetland studies, analysis is complicated by the hydrodynamic diversity in the system as well as by the difference in behavior of sand, silt, and clay particles. The cohesive characteristics of the clay and fine silt particles further complicate the analysis. Vegetation complicates the physical analysis of the deposition and erosion processes, as well as the transport process by altering the turbulent structure of flow when compared to "normal" boundary roughness dominated flows. In addition, the new "organic" sediment class is introduced. Organic sediments have both physical and chemical influences on sedimentation processes. Turbidity is a condition to be reckoned with in wetland systems and it has not received a great deal of attention analytically in existing sedimentation studies. Aquatic life in the wetland system can introduce turbidity, affecting light penetration and aquatic plant growth. The additional energy source due to aquatic life is one not commonly addressed in sedimentation studies. Finally, the presence of aquatic life may make boundary sediments more difficult to erode compared with the more biologically sterile riverine and flume systems which provided the coefficients for erosion functions currently in use.

APPLICATION IN WETLANDS: These and other factors complicate sedimentation investigations in the wetland environment. However, by carefully identifying goals and objectives, existing technology can give valuable insight into the longevity of a wetland as it responds to the inflowing sediment material. Also, existing technology can give valuable insights into the performance of project features as man attempts to work with and manage the wetland systems.

The Waterways Experiment Station is presently developing and distributing a system of PC based computer programs which calculate hydraulic parameters, sediment transport rates, and long term sediment yields. This application package will be useful for studying the finer silt and clay sediments commonly found in wetland environments, as well as coarser sand and gravel size sediments which occur in the inflowing or exiting channels. The package is called "Hydraulic Design Package for Channels (SAM)" (Thomas, *et. al.*, 1993).

CONCLUSIONS: Sedimentation studies have traditionally focused on riverine, reservoir, or estuarine systems. By recognizing the controlling physical similarities and differences between wetland and other hydrologic systems, application of the appropriate physical description of erosion, entrainment, transport, deposition, and compaction processes is possible.

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Engineering Description of Wetland Soils

PURPOSE: This technical note provides guidance for describing soils as part of the site evaluation and soil survey as an aid to identify wetland soils, to delineate wetland areas, and to determine construction properties required for wetland engineering. It provides guidance on how to describe wetland soils by field expedient and laboratory procedures. A field expedient description is useful to obtain a preliminary identification of soils and to determine preliminary engineering properties. Laboratory procedures accurately identify the soils and provide the best evaluation of engineering properties from soil description data. Evaluation of engineering properties is not within the scope of this technical note. The information supplements the design sequence contained in WRP Technical Note WG-RS-3.1.

BACKGROUND: Wetland soils typically include hydric sediments with an organic component of decomposed plant material (peats and mucks). A hydric soil contains abundant moisture and under wetland conditions will periodically be in a reduced state containing limited oxygen and a high water table. Sediments are materials that are deposited or settle to the soil surface from an overlying body of water. The organic material can influence soil parameters. Organic soils are readily identified by their color, odor, spongy feel and frequently by a fibrous texture.

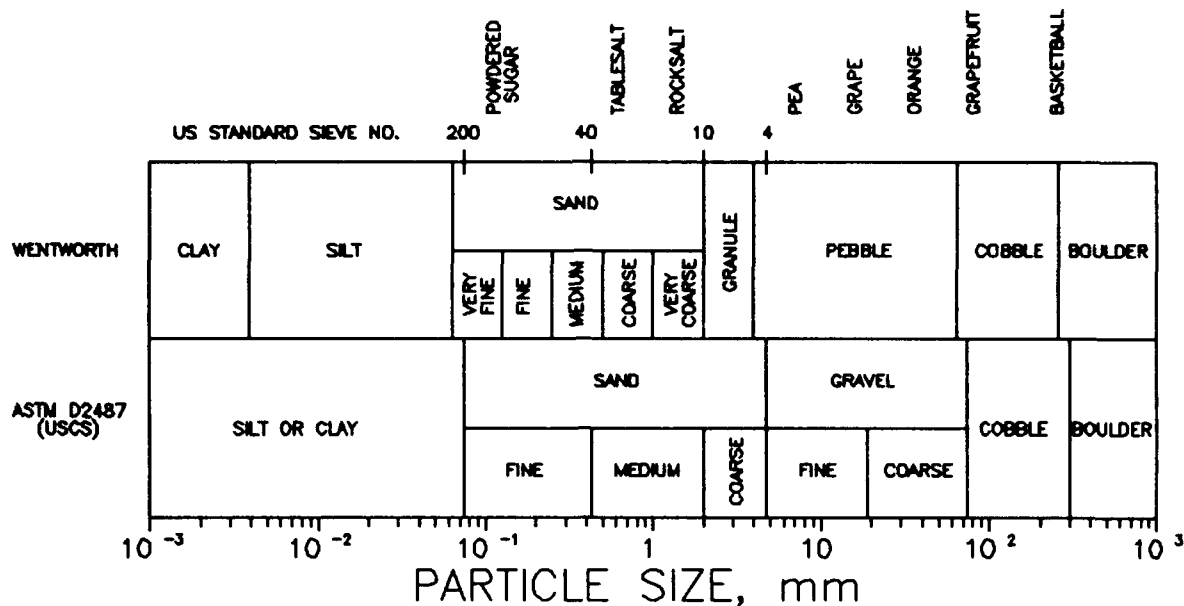
Diagnostic horizons of wetland soils include primitive entisols (E1), young inceptisols (I2), and mollisols (M1). Entisols (E1) are weakly developed wet soils with only A (exposed soil surface) and C (underlying parent material) horizons. The A horizon is young because of material deposited by water or some other agent. The A horizon will probably be a black, thick, fertile (mollic) or less fertile (umbric) soil. Inceptisols (I2) are usually moist immature soils commonly found in depressions where soil development is slowed by lack of periodic drying. Mollisols (M1) are found under wet grasslands with dense, fibrous root systems leading to a thick, dark, humus-enriched A horizon.

The thrust of the engineering description should be to identify soil from the texture; i.e., relative size, shape, and hardness of soil particles. The soil description with some information on mass (density, void ratio, water content) properties is sufficient to estimate a typical range of in situ or compacted soil properties for engineering applications.

Wetland soils are often sands with silts and clays. Particle sizes will typically be less than 4.75 mm (No. 4 US Sieve), according to the Wentworth (Müller 1967) or ASTM D 2487 (Unified Soil Classification System, USCS), Table 1. Table 2 identifies soil in terms of group symbols and typical group names by a field expedient procedure that uses the USCS. Soils possessing characteristics of two groups are designated by combinations of group symbols. For example, a GW-GC soil is a well-graded gravel-sand mixture with clay binder. A wetland soil may contain some sands with group symbols SW, SP, SM, and SC and may also contain silts and clays with group symbols ML, CL, OL, MH, CH, OL, and even may contain PT. A wetland soil will usually not contain any gravels.

Soft, compressible, fine-grained soil such as organic silt (OL), organic clay (OH), normally consolidated plastic clay (CH), peat (PT) or muck are undesirable for supporting embankments, roads, or other structures. Lean clays (CL) with plasticity index $PI \leq 12$ and liquid limit $LL \leq 35$, sands

Table 1. Grain Size Classification of Soils



(SC, SM-SC, SM, SP, SW), and gravels (GW, GP, GM, GC) usually provide the best soils for construction. Disturbed soil samples are required for an engineering description. Surface soils may be readily obtained by digging a small test pit with a pick and shovel or excavating a large test pit or trench with a backhoe, scoop, clamshell bucket or other mechanical equipment. Subsurface soil samples may be obtained by hand or machine-operated augers, piston, and other samplers (EM 1110-2-1907).

FIELD EXPEDIENT DESCRIPTION: An approximate description of wetland soils may be made in the field by observation and tests with portable equipment to determine the parameters given below. Equipment required to complete a field expedient description of soils is given in Table 3.

- **Acid test.** This test can determine the presence of calcium carbonate in the soil. Calcium carbonate is normally desirable because of the cementing action it provides and the soil strength that can be added to compacted soil over time. This test permits a better understanding of abnormally high strength values of fine-grained soils that are tested in-place. The test is conducted by placing a few drops of hydrochloric acid on a piece of the soil. A fizzing reaction (effervescence) indicates the presence of calcium carbonate.
- **Bite test.** This test is useful for identifying sand, silt, or clay. Sands grate harshly between the teeth, while silts feel gritty. Clays are not gritty, but feel smooth and powdery like flour.
- **Breaking test.** A pat of minus No. 40 sieve fraction is molded to 13 mm (1/2 in.) thickness by 32 mm (1-1/4 in.) diameter in the wet plastic state and allowed to dry completely. An attempt to break the thoroughly dried pat is made by using the thumb and forefingers of both hands. Avoid breaks along shrinkage cracks because these will not indicate the true breaking strength. The soil is roughly described as follows:

Table 2. Field Expedient Soil Classification (Data from Table 2-1 of FM 5-541, "Military Soils Engineering")

Major Divisions	Minor Divisions	Group Symbol	Typical Group Names and Description
Coarse-grained: Particles less than 75 mm (3 in.) and more than half larger than No. 200 sieve	Gravels: More than half larger than No. 4 sieve	GW	Well-graded gravels, gravel-sand mixtures; wide range of sizes with few or no particles less than No. 200 sieve
		GP	Poorly graded gravels or gravel-sand mixtures; predominantly one size with few or no particles less than No. 200 sieve
		GM	Silty gravels, gravel-sand-silt mixtures; nonplastic particles less than No. 200 sieve (see ML below)
		GC	Clayey gravels, gravel-sand-clay mixtures; plastic particles less than No. 200 sieve (see CL below)
	Sands: More than half smaller than No. 4 sieve	SW	Well-graded sands, gravelly sands; wide range of sizes with few or no particles less than No. 200 sieve
		SP	Poorly graded sands or gravelly sands; predominantly one size with few or no particles less than No. 200 sieve
		SM	Silty sands, sand-silt mixtures; nonplastic particles less than No. 200 sieve (see ML below)
		SC	Clayey sands, sand-clay mixtures; plastic particles less than No. 200 sieve (see CL below)
Fine-grained: Particles less than No. 40 sieve and more than half smaller than No. 200 sieve	Silts and Clays: liquid limit less than 50 percent	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity; none to slight dry strength; quick to slow dilatancy, no toughness
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays; medium to high dry strength, none to very slow dilatancy, medium toughness
		OL	Organic silts and organic silty clays of low plasticity; slight to medium dry strength, slow dilatancy, slight toughness
	Silts and Clays: liquid limit less than 50 percent	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts; slight to medium dry strength, slow to no dilatancy, slight toughness
		CH	Inorganic clays of high plasticity, fat clays; high to very high dry strength, no dilatancy, high toughness
		OH	Organic clays of medium to high plasticity, organic silts; medium to high dry strength, none to very slow dilatancy, slight to medium toughness
Highly Organic		PT	Peat and other highly organic soils; readily identified by color, odor, spongy feel and frequently by a fibrous texture

* See text for definitions of dry strength, dilatancy, and toughness.

Table 3. Equipment for Field Expedient Soil Classification	
Equipment	Remarks
No. 40 U.S. standard sieve and, if available, No. 4 and No. 200 sieves	The breaking, dilatancy, dry strength, ribbon, roll, and toughness tests are performed on material passing the No 40. U.S. standard sieve. Any screen with about 40 openings per lineal inch is useful. A No. 4 sieve is useful for separating gravel and a No. 200 sieve is useful for separating fines.
Pick and shovel	Entrenching tools are required for obtaining soil samples. A hand auger should be available for obtaining samples from depths more than a few feet below the surface.
Spoon	The spoon is used to mix water with cohesive soil and to obtain a desired consistency. The consistency desired is often like that of putty. If too dry, water must be added and if sticky, the soil should be spread out in a thin layer and allowed to lose some moisture by evaporation.
Pocket knife	A pocket knife is required for obtaining samples and trimming them to the desired size.
Small mixing bowl	Cup or other small container with a rubber-faced or wood pestle are required for pulverizing fine-grained portions of the soil.
Heavy paper	Several sheets of heavy paper are required for rolling samples.
Pan and heating element	A pan and heating element are required to dry samples for sieve analysis and to determine water content. Drying by sunlight is adequate for performing the field expedient tests and classification.
Balances or scales	Scales are required for weighing samples.

CH - Soil cannot be broken or powdered or broken with great effort, but not powdered

CL - Soil can be broken and powdered with some effort

ML, MH, or CL - Soil easily broken and readily powdered

ML or MH - Soil crumbles and powdered when picked up in the hands

- **Color.** The color distinguishes between different strata and assists the identification of the type of soil. Color classes are chroma and achroma with brilliance, hue, and saturation attributes. Chroma colors are reds, greens, purples, browns, and pinks. Achroma colors are black, white, and grays intermediate between black and white. Brilliance measures the difference between dark (low brilliance) and light (high brilliance) colors or grays. Hue measures the difference between separate colors. Saturation measures the degree of vividness of the hue or the difference from gray. High brilliance light gray, olive green, brown, red, yellow, and white are generally associated with inorganic soils. Red, yellow, and yellowish brown colors may be caused by iron oxides. White to pinkish colors may indicate silica, calcium carbonate, or aluminum compounds. Gray, brown, and black colors indicate organic, fine-grained colloidal (OL, OH) soils. Grayish blue, gray, and yellow mottled colors indicate poor drainage. Wetland soils in a reduced state typically have a dark, gray, mottled appearance with 2 or less chroma colors.
- **Dilatancy.** A pat of the minus No. 40 sieve fraction of moist soil is prepared with a volume of about 8.2 cc or 1/2 cu in. Add enough water, if necessary, to make the consistency of the soil soft or like a putty, but not sticky. Place the pat in the open palm of one hand and shake

horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of the appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in the soil. Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

- **Geophysical tests.** Geophysical exploration by seismic, electrical, magnetic, and gravity methods is useful during the site evaluation to assist with identification of the soil profile and the location and thickness of the various strata. These tests allow rapid coverage of large areas at a much smaller cost than conventional equipment. Electrical and magnetic methods are influenced by salinity of the water and could reduce their usefulness in coastal wetlands. Definite interpretation of the results is often uncertain and should be applied only with other subsurface exploration (Das 1984, Telford, et al 1988).
- **Grain shape.** The grain shape influences soil stability. Irregular, angular particles increase frictional resistance to displacements from applied loads compared with rounded particles. Irregular particles also cause interlocking between grains to increase frictional resistance and strength.
- **Odor.** Sense of smell or fragrance. The odor may be increased by heating the soil sample over an open flame. Organic OH and OL soils have a distinctive, musty, slightly offensive odor. A rotten egg odor is an indicator of a hydric soil and a wetland.
- **Ribbon test.** A pat of the minus No. 40 sieve fraction of soil is molded to the consistency of putty without being sticky, adding water or drying if necessary. The soil is rolled by hand on the heavy paper to about 13 to 19 mm (1/2 to 3/4 in.) diameter and about 8 to 13 cm (3 to 5 in.) long. The material is placed in the palm of the hand and starting with one end, the roll is flattened to form a ribbon 6 to 13 mm (1/4 to 1/2 in.) thick by squeezing it between the thumb and forefinger. The soil should be handled carefully to form the maximum length of ribbon that can be supported by the cohesive properties of the soil. If the soil holds together for a length of 20 to 25 cm (8 to 10 in.) without breaking, the material is of high plasticity (CH).
- **Roll test.** A pat of the minus No. 40 sieve fraction of soil is molded to the consistency of putty without being sticky, adding water or drying if necessary. The sample is rolled rapidly into a thread 3 mm (1/8 in.) in diameter. Materials which cannot be rolled into this thread at any water content are nonplastic or of low plasticity (ML or MH). If the soil can be rolled into a thread, then the degree of plasticity is determined as follows:

CH - Soil may be remolded into a ball and the ball deforms under extreme pressure by the fingers without cracking or crumbling.

CL - Soil may be remolded into a ball, but the ball will crack and easily crumble under finger pressure.

CL, ML, or MH - Soil cannot be lumped together into a ball without completely breaking up.

OL or OH - Soils containing organic materials or mica particles will form soft spongy threads or balls when remolded.

- **Slaking test.** This test assists in determining the quality of shales and other soft rocklike materials. The material is placed in the sun or in an oven to dry, and then allowed to soak in water for at least 24 hours. Materials that slake appreciably are undesirable for construction.
- **Toughness test.** A pat of the minus No. 40 sieve fraction of soil is prepared with a volume of about 13 mm (1/2 in.) on a side and molded to the consistency of putty without being sticky, adding water or drying if necessary. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about 3 mm (1/8 in.) diameter. The thread is then folded and rerolled repeatedly. During this manipulation the water content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached. After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles. The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line of the plasticity chart (see FM 5-541 or ASTM D 2487). Highly organic clays have a very weak and spongy feel at the plastic limit.

LABORATORY DESCRIPTION: A precise description of wetland soils may be accomplished by the USCS. USCS is a precise system for classifying mineral and organo-mineral soils for engineering purposes based on laboratory determination of Atterberg limits and particle-size distribution. The ASTM version of the USCS is given as standard test method D 2487. Knowledge-based computer systems such as CLASS-92 (Bakeer 1992) expedite an efficient engineering description by the USCS. CLASS (Morse and Bakeer 1990) may be used to convert between Visual, USCS, ASTM, and AASHTO systems. Liquid limit, plasticity index, and the particle size distribution are sufficient to describe soil by the USCS.

- **Atterberg limits.** Indices expressed in terms of the water content (w) of soil in percent that are useful for general characterization of soil, particularly to evaluate the degree of plasticity and compressibility:

Liquid limit LL, percent - water content between the liquid and plastic state. LL may be determined by ASTM D 4318.

Plastic limit PL, percent - water content between the plastic and semisolid state. PL may be determined by ASTM D 4318.

Plasticity index PI, percent - difference in water content between the liquid limit and plastic limit, $PI = LL - PL$.

- **Particle size distribution** - determines the proportions by mass of a soil or fragmented rock in specified ranges of particle sizes. D_n is the diameter of soil particles that is (n) percent finer by weight; e.g., D_{10} is the particle diameter at which 10 percent of the material is finer by weight. Particle size distribution may be determined by standard test method ASTM D 422. Refer to ASTM D 2487 for other methods of gradation analysis. The following gradation ratios are also applied by the USCS to classify soil:

Coefficient of curvature $C_c - (D_{30})^2 / (D_{10} \cdot D_{60})$.

Coefficient of uniformity $C_u - D_{60} / D_{10}$.

Soils with C_u between 1 and 3 and C_u greater than 4 are well-graded clean gravels, GW, provided that the fines smaller than No. 200 mesh are less than 5 percent by weight. Soils with C_u between 1 and 3 and C_u greater than 6 are well-graded clean sands, SW, provided that fines smaller than No. 200 mesh are less than 5 percent by weight.

- Liquidity index LI, percent. Ratio of water content (w) minus PL to PI, $(w - PL)/PI$. LI close to and exceeding unity indicate normally consolidated soils, recently deposited sediments, and a potential of being wetland soils. LI exceeding unity indicates soil on the verge of being a viscous liquid. LI close to or less than zero indicates overconsolidated, desiccated soil and soil with high foundation strength.
- Shrinkage limit SL, percent. Component of Atterberg limits that is the water content between the solid and semisolid state; least water content at which the degree of saturation is 100 percent. SL may be determined by Appendix IIIB of EM 1110-2-1906. Water content near or less than SL indicates an overconsolidated, desiccated soil.
- Specific gravity of solids G_s . Ratio of mass (grams or g) in air of a given volume of solids at a stated temperature to the mass in air of an equal volume of distilled water at the same temperature. $G_s = \gamma_s/\gamma_w$, where γ_s = ratio of the solid mass to the volume of the solid mass, g/cc, γ_w = unit mass of water at 4°C, 1 g/cc. G_s may be determined by standard test method ASTM D 854. Estimates of G_s are given in Table 4. Typical G_s is 2.67 for sands and 2.70 for clays. Smaller G_s indicates soils with more organic material.

Table 4. Specific Gravities of Some Soils (After Bowles 1988)

Soil Type	Specific Gravity G_s
Sand	2.65 - 2.68
Silty sand	2.67 - 2.70
Inorganic clay	2.68 - 2.75
Inorganic silt	2.62 - 2.68
Soils with micas and iron	2.75 - 3.00
Organic clay	2.58 - 2.65

The specific gravity is used to determine mass properties such as the density, void ratio, and degree of saturation.

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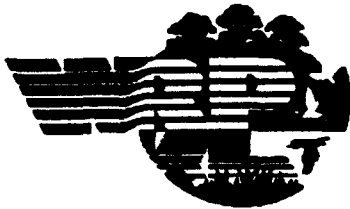
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Engineering Properties of Wetland Soils

PURPOSE: This technical note provides guidance for evaluating the engineering properties of wetland soils required for wetland engineering. Mass properties are also included to complete evaluation of the engineering properties. Engineering of wetland soils includes development and application of efficient procedures for the design, establishment and construction, restoration, operation, and maintenance of wetlands. This information supplements material outlined in WRP Technical Note WG-RS-3.1.

BACKGROUND: Engineering properties are strength, compressibility, and permeability. These properties influence the critical soil processes that govern the performance of a wetland when a force is applied to the soil.

Critical soil processes include the compaction characteristics of fill materials used to construct dikes, slope stability, and settlement of earth dikes containing water and soils in wetlands; compaction characteristics of wetland soils, sedimentation, and erosion characteristics of wetland soils, and the flow of water through wetlands and dikes. These processes influence water and sediment storage capacity, water quality and flow, and erosion from and collection of sediments on the surface of submerged wetland soils. The strategy for determining procedures for construction or restoration, operation, and maintenance of wetlands is based on the critical soil processes evaluated from the engineering properties of wetland soils.

Preliminary or approximate engineering properties of wetland soils may be evaluated from classification data with some information on mass properties such as density, void ratio, and water content. The engineering classification of wetland soils may be determined by field expedient and laboratory procedures given in WRP Technical Note SG-RS-1.1, *Engineering Description of Wetland Soils*.

Information required to determine engineering properties for final design, restoration, construction, and maintenance of wetlands may be provided from results of detailed site evaluation and soil survey. The survey should include in-situ soil tests such as cone penetration (CPT) and standard penetration (SPT) and laboratory tests performed on undisturbed soil samples. Hand-operated piston, Shelby push tubes, rotary, and samplers are available for retrieving disturbed and undisturbed soil samples as outlined in EM 1110-2-1907.

IDENTIFICATION OF MASS PROPERTIES: Mass properties are the density, void ratio, and water content of the soil.

- Density, g/cc. Mass per unit volume of material:

Wet density γ - in-place total mass per unit total volume of material. γ may be determined by ASTM D1556, D2167, or portable field methods given in Appendix E of EM 1110-2-1907.

Dry density γ_d - mass of solid particles per total volume of material. γ_d may be determined from $\gamma/(1 + w/100)$ where "w" is the water content on a dry weight basis in percent.

Saturation density γ_{sat} - wet density at which the pore water pressure of a normally consolidated undisturbed soil is zero. γ_{sat} of a freshly deposited (normally consolidated) sediment may be estimated by $(G_s + e_{SL})\gamma_w/(1 + e_{SL})$ where e_{SL} = void ratio at the saturation limit, $\approx 1.0 + 0.0589PI$. $\gamma/\gamma_{sat} < 1.3$ indicates possible wetland soils. γ_w = unit mass of water, 1 g/cc. G_s = specific gravity of solids.

- Desiccation limit e_{DL} . Least void ratio of soil caused by desiccation. $e_{DL} \approx 1.6 + 0.0106PI$ and it occurs approximately at a degree of saturation of 60 percent. Void ratios near e_{DL} indicate an overconsolidated, desiccated soil.
- Liquidity index LI, percent. Ratio of water content w minus PL to PI, $(w - PL)/PI$. LI close to and exceeding unity indicate normally consolidated soils, recently deposited sediments, and a potential of being wetland soils. LI exceeding unity indicates soil on the verge of being a viscous liquid. LI close to or less than zero indicates overconsolidated, desiccated soil and soil with high foundation strength.
- Void Ratio, e . Ratio of the volume of void space to the volume of solid particles in a given soil mass. $e = (G_s/\gamma_d)\gamma_w - 1.0$ where G_s = specific gravity, γ_d = dry density, g/cc, and γ_w = unit mass of water, 1 g/cc.
- Water content w , percent. Ratio of the mass of water contained in the pore spaces of soil to the mass of solid dry material expressed as a percentage. Soil water content may be evaluated in the laboratory by ASTM D2216 or microwave oven method D4643. The natural water content of in situ soil can indicate drainage characteristics and nearness to a water table. The optimum water content of compacted fill materials allows compaction to the greatest density and strength.

Field expedient natural water content test. A piece of undisturbed soil is tested by squeezing it between the thumb and forefinger to determine its consistency; i.e., hard, stiff, brittle, friable, sticky, plastic or soft. The soil is then remolded by working it in the hands, and changes, if any, are observed. Clays which turn almost liquid on remolding are probably near or above the liquid limit. If the clay remains stiff and crumbles upon being remolded, the natural water content is below the plastic limit.

Field expedient optimum water content (OMC) test. A golf ball size of soil is molded by hand and squeezed between the thumb and forefinger. If the ball shatters into several fragments of rather uniform size, the soil is near or at OMC. If the ball flattens out without breaking, the soil is wet of the OMC. If the soil is difficult to roll into a ball or crumbles under very little pressure, the soil is dry of the OMC.

IDENTIFICATION OF ENGINEERING PROPERTIES: Engineering properties are the strength, compressibility, and permeability parameters of the soil.

- Strength properties. Strength parameters define the ability of soil to support dikes, retaining walls, pavements, and other structures and to resist erosion from flowing water. The shear strength τ is given by Coulomb's equation in terms of strength parameters c and ϕ , $\tau = c + \sigma_n \tan \phi$ where σ_n is the component of stress normal to the shear plane. The shear stress τ is tangent to the shear plane.

c , cohesion, kPa - shear resistance at zero normal stress or the intrinsic shear strength. A perfectly cohesive soil has strength only from cohesion where $\phi = 0$. The shear strength of a clay when undrained is $c = C_u$ where C_u is the undrained shear strength. The compressive strength q_u is twice the undrained shear strength. q_u is usually determined on specimens not confined by any applied stress.

ϕ , friction angle, degrees - The angle of internal friction or angle of shear resistance is the angle between the axis of normal stress σ_n and tangent to the mohr envelope at a point representing a given failure stress condition for the soil. A perfectly cohesionless soil or sand has strength only from friction where $c = 0$.

- Compressibility properties. These properties include both elastic and consolidation parameters. Elastic parameters define the ability of soil to resist elastic deformation and settlement from applied forces. Elastic deformation occurs almost immediately and accounts for nearly all or most of the settlement in cohesionless soil. Consolidation parameters define the ability of saturated soil to resist settlement or heave caused by applied forces. Changes in applied forces instantly cause corresponding changes in pore water pressure leading to the flow of water into or out of the soil. The resulting consolidation from changes in the water content occurs over time depending on the ability of the soil to conduct water (permeability properties). Consolidation in cohesive soil occurs over a relatively long time and often accounts for most of the settlement.

E , modulus of elasticity, kPa - This elastic modulus of deformation is the ratio of stress to strain for a soil under given loading conditions. E is often used to determine immediate settlement from static loads.

G , shear modulus, kPa - the shear modulus is the ratio of shear stress to shear strain under given loading conditions. G is often used to determine deformation or settlement from dynamic loads or vibrations. G is related to E by Poisson's ratio ν , $G = E/[2(1 + \nu)]$. Poisson's ratio is the ratio between linear strain changes perpendicular to and in the direction of a given uniaxial stress change.

C_c , compression index - The compression index is the slope of the linear portion of the pressure-void ratio curve on a semi-log plot. The linear portion occurs at pressures exceeding the maximum past pressure σ_p that had been applied to the soil.

C_r , recompression index - The recompression index is the slope of the pressure-void ratio curve on a semi-log plot following removal of the maximum pressure σ_p that had been applied to the soil, but at pressures that exceed the vertical overburden pressure σ_v that was applied to the in situ soil.

Overconsolidation ratio OCR. The OCR is the ratio of preconsolidation pressure σ_p' to the effective overburden pressure σ_v' . $\sigma_v' = \sigma_v - u_w$, σ_v = total overburden pressure, u_w = pore water pressure, kPa. OCR of a normally consolidated soil is unity. OCR of overconsolidated soil exceeds unity. Wetland soils are often normally consolidated.

- Permeability Properties. Permeability is a property of a mass soil that controls the rate of flow of water Q through the soil. Permeability is influenced by the void ratio, continuity of voids, and fissures that may be caused by drying and wetting weather cycles.

k , coefficient of permeability, cm/sec - The permeability controls the flow of water Q through a cross-section area A of soil depending on the hydraulic gradient i , $k = Q/(iA)$. The hydraulic gradient is $\Delta h/L$ where Δh is the difference in height of the water columns in a standpipe inserted at the entrance end and at the exit end of a filter bed and L is the length of the filter bed between the standpipes.

c_v , coefficient of consolidation, cm^2/sec - c_v is used in the Terzaghi theory of consolidation containing the physical constants of a soil affecting its rate of volume change,

$$c_v = \frac{k(1+e)}{\gamma_w a_v}$$

where e = void ratio, γ_w = unit weight of water, 1 g/cc, a_v = coefficient of compressibility, cm^2/g .

EVALUATION OF ENGINEERING PROPERTIES: Engineering properties may be approximated from classification data or evaluated from in situ and laboratory soil tests.

- **Strength parameters.** Angle of internal friction ϕ , deg. Angle between the normal stress axis and tangent to the Mohr envelope at a point representing a given failure stress of the soil. ϕ is required to evaluate the slope stability and bearing capacity of cohesionless soil or sands. ϕ is usually estimated from correlations of field soil tests such as cone penetration (CPT) or standard penetration (SPT) tests because undisturbed boring samples for laboratory tests are rarely obtainable for sands. Table 3-1 in EM 1110-1-1905 provides correlations of ϕ with relative density, CPT (ASTM D 3441), and SPT (ASTM D 1586). Figure 1 correlates the soil classification and the dry unit weight γ_d with ϕ when CPT or SPT data are not available.

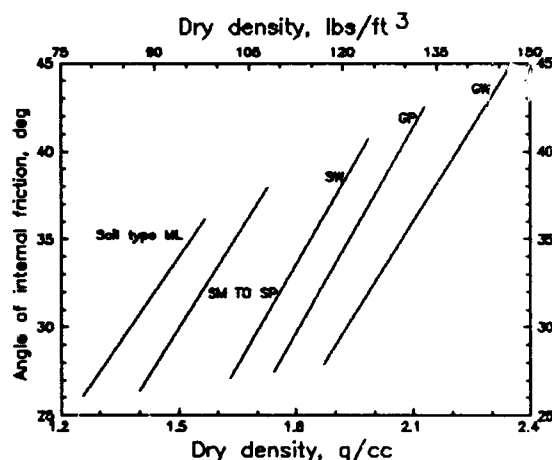


Figure 1. Strength characteristics for cohesionless soils

Unconfined compressive strength q_u , kPa. Strength at which an unconfined cylindrical specimen of soil will fail in a simple compression test. A simple portable field device for estimating q_u , the pocket penetrometer, is a small, hand-operated, spring-calibrated penetrometer for estimating the engineering consistency of cohesive, fine-grained soils, Table 1. This device is pushed into soil surfaces and it is calibrated to determine q_u in kilograms per square centimeter ($1 \text{ kg/cm}^2 = 100 \text{ kPa}$). The apparatus and procedure are described by Bradford (1986). Clays of medium or softer consistency are normally consolidated and may be in wetlands. Stiff and harder clays are overconsolidated.

Vane torque T_v , N·m. The turning moment required to shear a cylindrical column of cohesive soil. The torque may be determined by a four-bladed vane device according to standard test method ASTM D 2573.

Undrained shear strength C_u , kPa. The maximum resistance to shear forces when pore pressures are not drained. C_u is required to evaluate slope stability and bearing capacity of cohesive soils. C_u may be estimated from results of the pocket penetrometer test as $1/2$ of q_u , the unconfined compressive strength. C_u may also be estimated from results of the field vane shear test by T_v/K_v where K_v is the vane constant. K_v depends on dimensions and shape of the vane (ASTM D 2573).

- **Compressibility properties.**

Compression index C_c . Slope of the linear portion of the pressure-void ratio curve on a semi-log plot. This parameter is required to evaluate settlement caused by consolidation of compressible soil. C_c may be estimated by $-0.156 + 0.411e + 0.00058LL$ (Al-Khafaji and Andersland 1992) where the correlation coefficient is 0.957 and standard error is 0.077 based on 72 data points. Refer to EM 1110-1-1904 for other correlations.

Elastic Young's modulus E_s , kPa. Ratio of vertical stress σ_v to the vertical strain caused by σ_v . E_s is used to estimate elastic settlement of soils according to procedures given in EM 1110-1-1904. E_s may be estimated from a general classification given in Table 2.

Table 1. Correlation of Consistency With Shear Strength of Cohesive Soil

Relative Consistency	Unconfined Compressive Strength q_u , kPa
Fluid mud	< 2
Very soft	2-25
Soft	25-50
Medium	50-100
Stiff	100-200

Table 2. Typical Elastic Moduli

Soil	E_s , kPa
Clay	
Very soft	500 - 5,000
Soft	5,000 - 20,000
Medium	20,000 - 50,000
Stiff, silty	50,000 - 100,000
Sandy	25,000 - 200,000
Shale	100,000 - 200,000
Sand	
Loose	10,000 - 25,000
Dense	25,000 - 100,000
Dense w/gravel	100,000 - 200,000
Silty	25,000 - 200,000

- **Permeability properties.**

Coefficient of permeability k , cm/sec. Rate of discharge of water under laminar flow through a unit area of a porous medium for a unit hydraulic gradient at a standard temperature, usually 20°C. k is required to evaluate the quantity and rate of fluid flow through soils. k is given from classification data by Table 3. k may be estimated by Figure 2 for sands from gradation data and void ratio e . k may be estimated for clays from $0.1C_v\gamma_w m_v$ where C_v = coefficient of consolidation, cm^2/sec , γ_w = unit mass of water, and m_v = coefficient of volume change,

kPa^{-1} ($1 \text{ cm}^2/\text{g} = 10 \text{ kPa}^{-1}$). C_v may be estimated from the liquid limit LL by Table 4. Undisturbed sediments not subject to wet/dry cycles should have C_v similar to those for virgin consolidation. Soil subject to wet/dry cycles should have C_v similar to soil subject to recompression. $m_v = 0.435C_e/[(1+e)\sigma_{mv}]$ where C_e = compression index and σ_{mv} = mean vertical stress on the soil in the field, kPa.

Table 3. Coefficient of Permeability by Soil Classification

Soil Type	k, cm/sec
GW-SW	$> 10^{-2}$
GP-SP	$5 \cdot 10^{-4} - 10^{-2}$
MP-OL	$10^{-5} - 5 \cdot 10^{-4}$
GF-SF-MH	$5 \cdot 10^{-7} - 5 \cdot 10^{-4}$
GC-SC-CL	$5 \cdot 10^{-7} - 10^{-5}$
CL-CH-OH	$< 5 \cdot 10^{-7}$

Table 4. Correlation of Liquid Limit with the Coefficient of Consolidation. (After Lambe and Whitman 1969)

LL, Percent	C_v , $\text{cm}^2/\text{second}$	
	Recompression	Virgin
30	0.035	0.005
60	0.0035	0.001
100	0.0004	0.0001

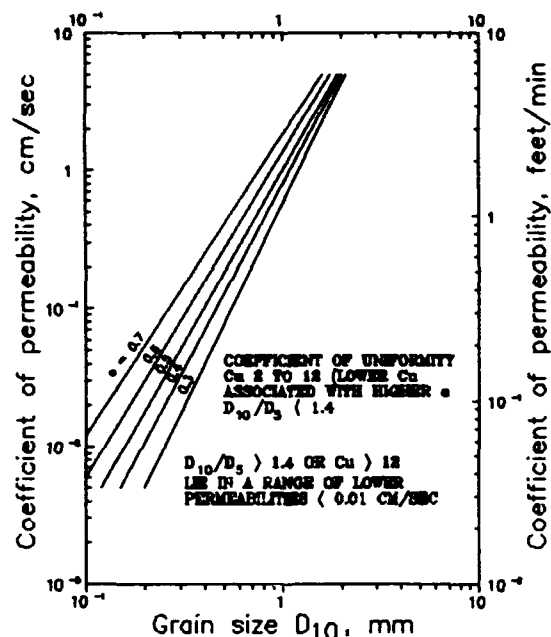
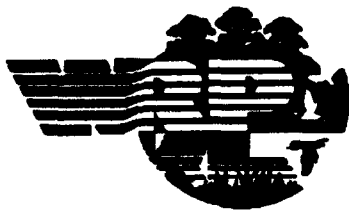


Figure 2. Permeability of sands and sand-gravel mixtures from void ratio and gradation data (After NAVFAC DM-7.1). e = void ratio; C_u = coefficient of uniformity, D_{60}/D_{10}

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Physiological Response to Flooding for Wetland Indicator Plants

PURPOSE: This Technical Note describes a general method that may help refine the indicator categories of some problematic wetland plant species within different geographic regions.

BACKGROUND: The U.S. Department of the Interior, Fish and Wildlife Service, publishes regional lists of plant species that occur in wetlands. These lists are compiled from literature, field data, comments received from biologists within each region, and the experience of regional review panel members. Each species within a region that occurs in wetlands is assigned a wetland indicator status based upon its frequency of occurrence in wetlands. Table 1 shows the estimated probability of occurrence for indicator categories for wetland plant species.

Wetland plant species with little field data or with broad ecological amplitude are difficult for regional review panels to categorize accurately, and are therefore problematic. Regional problematic species, when repeatedly part of the hydrophytic vegetation determination, can leave the delineator uncertain about the wetland determination. There is a need to develop method(s) to refine indicator status of problematic species.

Species that have a higher probability of occurrence in wetlands likely exhibit a higher tolerance of wetland conditions, i.e., water saturated, chemically reduced soils. Differential physiological responses to flooding may provide a potential method to refine the indicator status of some problematic wetland plant species. The method presented in this technical note uses photosynthetic response to inundation by wetland plant species that have been identified as having reliable indicator status as a baseline for comparison.

METHODS: Species with dependable indicator status were selected by biologists who routinely perform wetland delineations within the geographic area of the U.S. Army Engineer District, Buffalo, NY. Plant species studied were *Typha latifolia* (Cattail), *Scirpus cyperinus* (Wool-grass), *Parthenocissus quinquefolia* (Virginia Creeper), and *Solidago nemoralis* (Gray Goldenrod). The indicator status assigned to these species by Reed (1988) is: Cattail (OBL), Wool-grass (FACW+), Virginia Creeper (FACU), and Gray Goldenrod (UPL). Live specimens of each species were collected, vegetatively propagated, and grown in the greenhouse. Plants were inundated in fiberglass tanks to 5 cm above the top of the pots. Most of the leaves were above the water. Photosynthesis and other gas exchange parameters were measured before inundation, and weekly after inundation. Control plants were not inundated. Measurements were made in the greenhouse under constant light intensity. Three replicate plants were measured for each of the control and inundated treatments.

RESULTS: Photosynthetic response of the plant species to inundation is presented in Figure 1. Day zero represents pre-inundation measurements. The OBL, FACW+ and FACU species showed an initial decline in photosynthetic rate associated with inundation (Fig. 1). Photosynthesis of both the OBL and FACW+ species recovered after seven days of inundation, while that of the FACU species continued to decline. Inundated FACU plants were dead after 30 days. Photosynthesis of the inundated OBL species recovered after two weeks and exceeded that of the non-flooded control plants.

Table 1. Probability of occurrence in wetlands and uplands of species with different wetland indicator status

Indicator status	% of frequency of occurrence in:	
	Wetlands	Uplands
OBL*	>99	<1
FACW	67-99	1-33
FAC	34-66	34-66
FACU	1-33	67-99
UPL	<1	>99

* In addition, the FACW, FAC, and FACU categories may be modified with '+' or '-' to indicate the higher or lower part, respectively, of the range of occurrence in wetlands for that category.

Although photosynthesis of the inundated FACW+ species also recovered after two weeks, it did not exceed that of the control. The response of the UPL species was difficult to characterize because of scatter in the data. The general decline in photosynthesis observed in control plants of all species may represent a response to elevated daytime greenhouse temperatures.

CONCLUSION: The responses of the OBL, FACW+ and FACU species were distinct, perhaps reflecting different levels of flooding tolerance. This preliminary study suggests that photosynthetic response to inundation may be helpful in refining the indicator status of some problematic wetland plant species. Additional species of each indicator status must be studied to verify and refine the trends observed here. A larger set of reliable baseline species of all indicator classes should be characterized. Then several problematic species should be tested and their responses compared to those of the baseline species.

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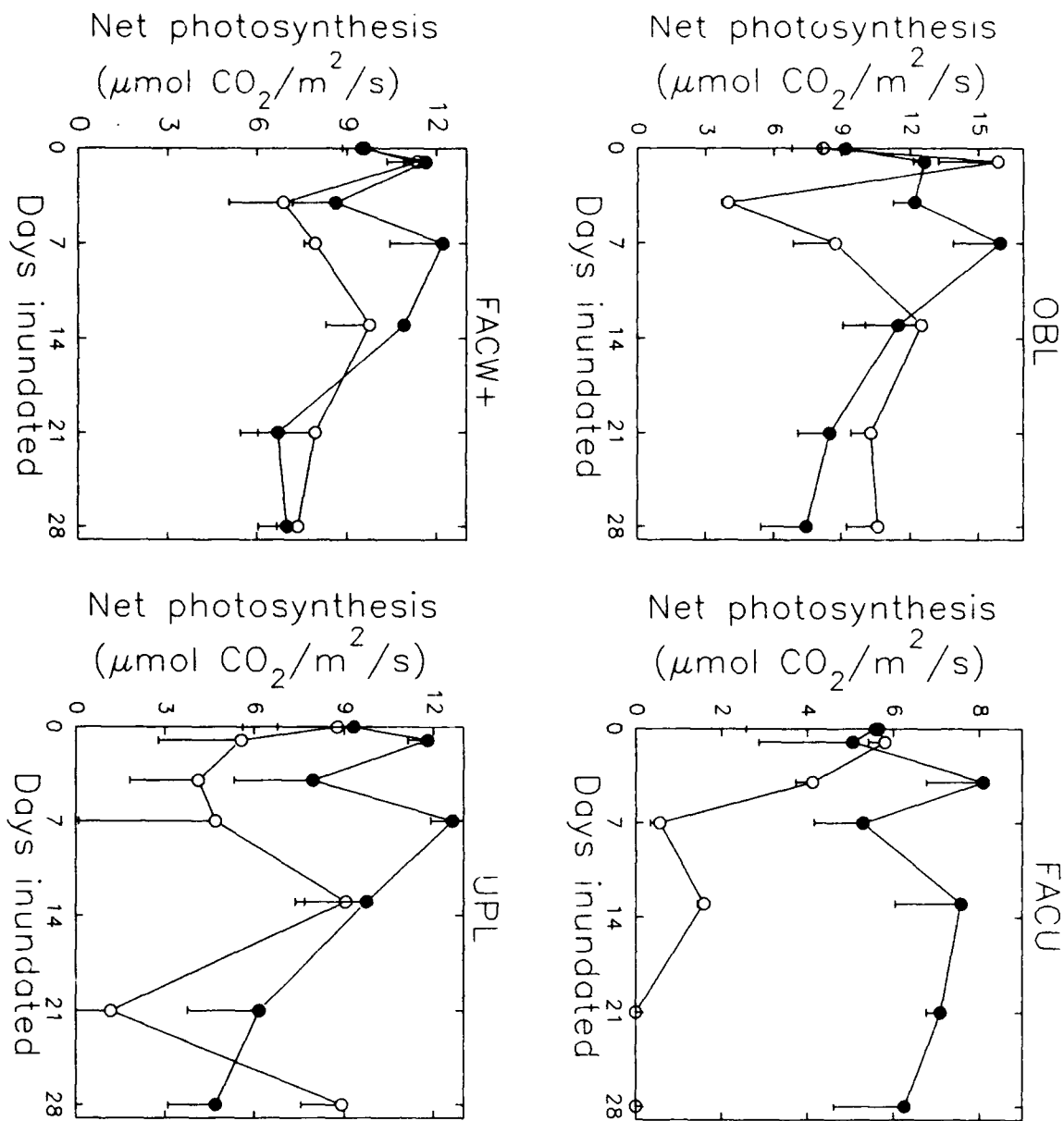


Figure 1. Net photosynthesis for four plant species exposed to inundation. OBL = *Typha latifolia*, FACW + = *Scirpus cyperinus*, FACU = *Parthenocissus quinquefolia*, and UPL = *Solidago nemoralis*. Open circles represent inundated plants, closed circles represent noninundated plants. Each circle represents the mean of three replicates. Vertical bars are standard deviations of the mean.



Design of Constructed Wetlands Systems for Nonpoint Source Pollution Abatement

PURPOSE: This technical note describes some basic considerations for design of constructed wetlands for controlling nonpoint source (NPS) pollution. A design sequence for constructed pollution abatement wetlands systems for NPS pollution is presented. Critical elements in the design sequence are identified. This technical note should be used as a conceptual design guide and in conjunction with other guidance provided in WRP Tech Notes HS-EM-3.1, HY-EV-5.1, HY-IA-5.1, HY-RS-3.1, SG-RS-3.1, VN-EM-3.2, WQ-EV-2.1, and WG-RS-3.1.

BACKGROUND: NPS pollution originates from rainfall/runoff events on agricultural and urban areas. Because rainfall/runoff events are stochastic processes that can be highly episodic in character, hydraulic and pollutant mass loadings associated with nonpoint source pollution are extremely variable. Most treatment systems designed for point source discharges are ineffective for NPS pollution because they cannot handle wide fluctuations in hydraulic loading and perform poorly when there are large fluctuations in pollutant loadings. Wetlands, on the other hand, dampen extremes in flow and pollutant loadings by storing water. In addition, wetlands have intrinsic abilities to retain, transform, and degrade a wide spectrum of waterborne pollutants (Mitsch and Gosselink 1986; Hammer 1990). Constructed wetlands located to intercept runoff, therefore, have potential for reducing NPS pollution.

ENVIRONMENTAL ENGINEERING DESIGN: Constructed Pollution Abatement Wetlands Systems (CPAWS) are vegetated water retention facilities designed, constructed, and operated to treat pollutants using physical, chemical, and biological processes intrinsic to wetlands. Successful CPAWS design for NPS pollution abatement differs from CPAWS design for point source pollution in that average flows and pollutant concentrations do not provide a sound basis for design. The basic problem is to capture and spread high flow, high contaminant concentration runoff in a wetland and retain the water long enough for wetland biogeochemical processes to degrade or remove pollutants. A quasi-theoretical design approach that combines empiricism with simplified theory is recommended. This approach is based on first order process kinetics described by Reed (1990), Rogers and Dunn (1992) and Dortch (1993). The design sequence (Fig. 1) includes the following elements.

- **Target Pollutants and Design Flows.** Successful design of CPAWS requires development of the proper hydraulic and biogeochemical conditions to remove pollutants of concern. Therefore, the first step in the design process should be identification of pollutants to be treated and the design storm or flow. Pollutants can be targeted based on sampling inflow, review of available data on water quality problems in the receiving water body, or evaluation of land uses and probable constituents in runoff. Different pollutants may require different designs. For example, herbicides require a longer retention time for removal than suspended solids. The design flow can be selected or determined from the design storm event. Two types of events are important, the maximum event to be treated and the extreme event the wetland must survive. The maximum event determines the size of the wetland and associated control structures. The extreme event determines the size of emergency flow structures. Selection of the appropriate event will depend on the project. Costs, target treatment, and available land are some factors to be considered in the selection.

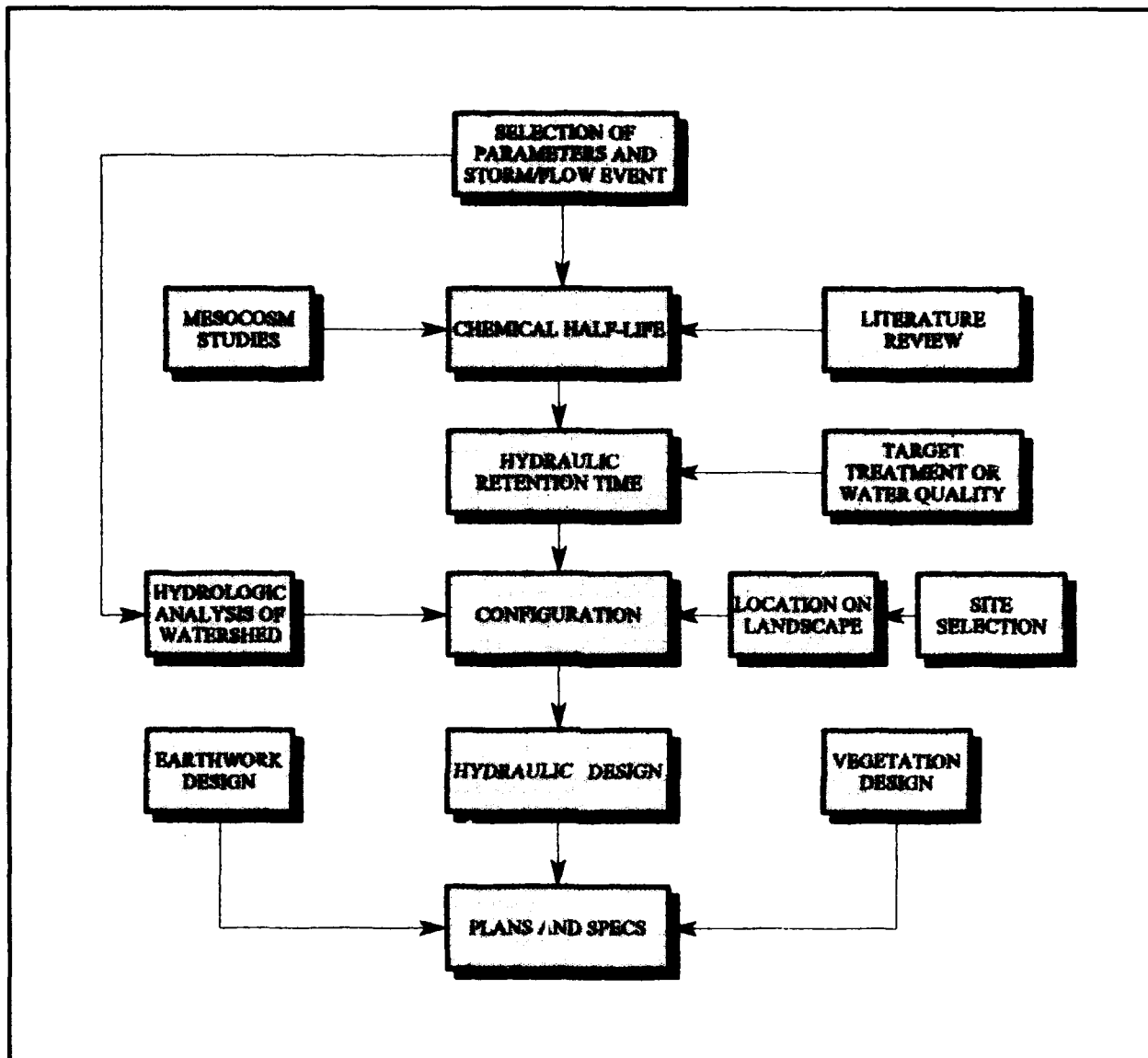


Figure 1. Design sequence for constructed pollution abatement wetland systems

- Chemical Half-life.** Application of first order process kinetics to wetlands involves an overall disappearance coefficient. First order disappearance coefficients can be expressed as chemical half-lives. Thus, one of the first steps in design is to estimate the half-life applicable to wetlands. This half-life is chemical dependent and is anticipated to vary with wetlands characteristics, such as vegetative cover, vegetation type, climatological conditions, and other factors. Literature values for chemical half-lives can be unreliable for CPAWS design because few of the available data were developed from wetlands studies. Wetlands specific removal efficiencies are available for nutrients, metals, and some other water quality parameters, but in many cases the corresponding hydraulic retention times are not available (Phillips et al. 1993). Both parameters are needed to obtain disappearance coefficients. Experimental wetlands mesocosm studies can be conducted that provide half-lives for specific chemicals and wetlands characteristics (Doyle, Myers, and Adrian 1993).

- **Hydraulic Residence Time (HRT).** As indicated in Figure 1, chemical half-life determines the HRT required to meet a target level of treatment. The HRT then becomes the basis for hydraulic design. HRT is the average time required for a parcel of water to pass through a wetland. If the design HRT is not achieved, the design level of treatment will not be achieved. The theoretical HRT of an idealized system is defined as

$$\text{HRT} = \frac{V}{Q}$$

where V is the volume of the wetland and Q is flow. However, this definition implies that the entire cross-sectional area is included in the flow and each parcel of water remains in the system for the same amount of time. This is seldom true or even approximately true for wetlands. Irregularly shaped, vegetated wetlands subjected to a variety of flow conditions tend to form channels that reduce effective HRTs to values substantially less than theoretical HRTs. This is commonly referred to as "short-circuiting". Designing the system to reduce or eliminate channels and maximize vegetative cover will spread flow, reduce short-circuiting, and increase effective HRT. Kadlec (1989) and Reed (1990) proposed methods to calculate HRTs for CPAWS used to treat wastewater streams. These methods adjust the HRT to account for the effects of vegetation. Kadlec (1989) also described techniques to account for rainfall and evapotranspiration, which can be important when dealing with relatively small flows. Potentially more important considerations for CPAWS used for NPS pollution abatement are selecting an appropriate storm event and routing flow through the wetland. A detailed hydrologic and flow routing study should be conducted for any project which entails significant expenditures.

- **Configuration.** After the design HRT has been determined, a wetlands configuration is chosen. A variety of wetlands configurations ranging from a single wetland to several wetlands in parallel or series or distributed over a landscape are possible (Fig. 2). In many cases, configuration is primarily a matter of land availability. For distributed CPAWS, a HRT should be calculated for each wetland. Since wetlands are shallow, total wetlands area is usually the design parameter adjusted to provide the needed HRT.
- **Hydrology.** To determine the wetlands area, a design flow must be established. This is accomplished by hydrologic analysis of the watershed or catchment (Richards 1993a). Hydrologic analysis should provide storm hydrographs for routing water, establishing stage-storage relationships, sizing inlet and outlet structures, and sizing the wetlands. In addition, runoff models are available for some NPS pollutants, such as pesticides, that can be coupled with a hydrologic analysis to provide information on the distribution of hydraulic and pollutant mass loadings in space and time. Distributions of hydraulic and pollutant mass loadings in space and time are needed to design distributed CPAWS for large watersheds. The design HRT may require revision if the runoff quantity/quality estimated by runoff models differs from that used in the initial calculation of HRT.
- **Vegetation.** Vegetation is a key component of treatment process effectiveness. Vegetation provides resistance to flow, spreads water, and facilitates sedimentation. Vegetation is the primary source of detritus and also provides a substrate for the periphyton community. In a wetlands, periphyton surrounding plant stems is a region of intense energy (chemical) and materials transfer. It is in the periphyton community that pesticides and other toxic organics are most likely to disappear or be degraded. Basic considerations for vegetative design of wetlands were described

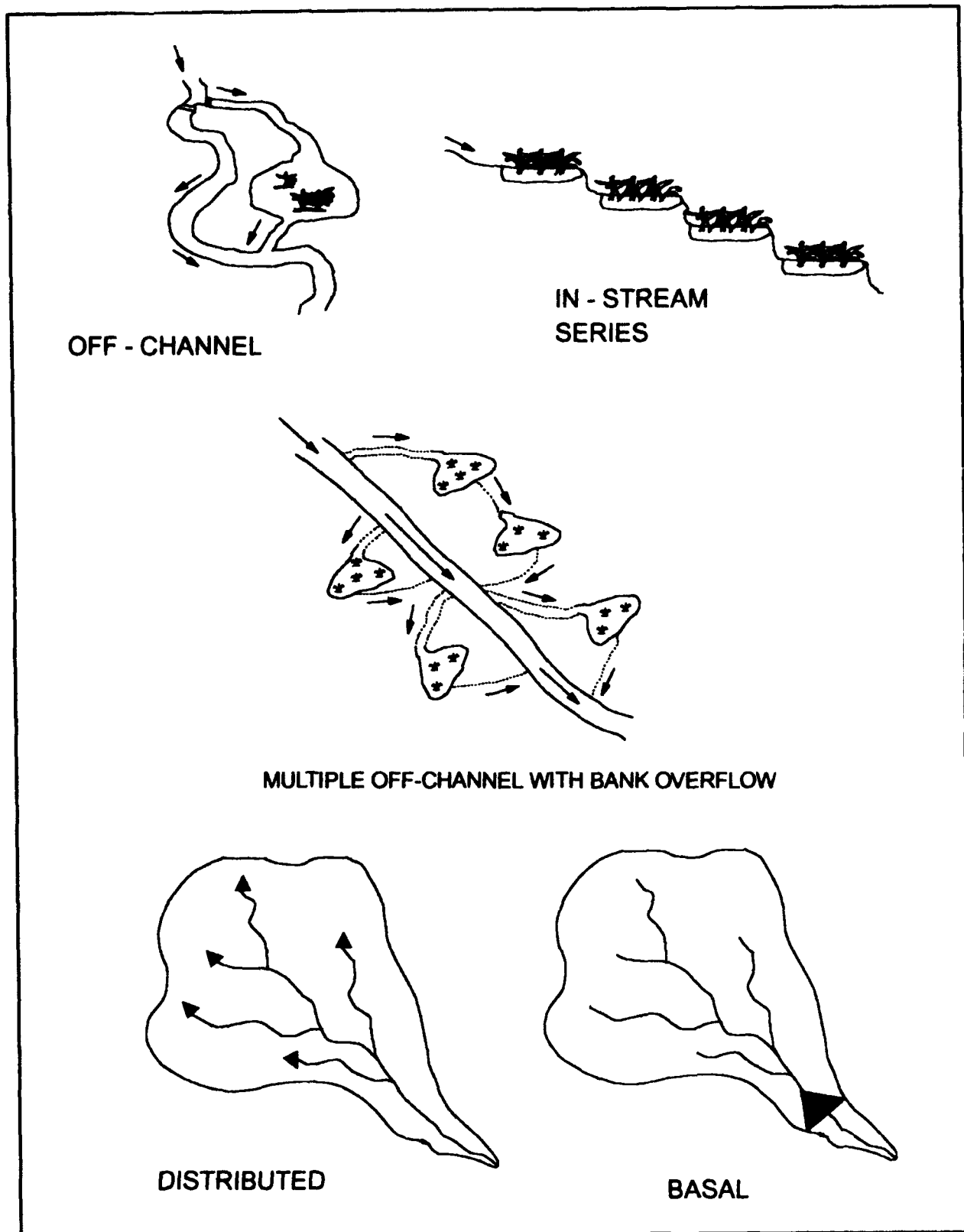


Figure 2. Selected Siting Alternatives for CPAWS

by Allen (1993). For CPAWS, development of the vegetation component to the maximum extent possible (consistent with hydraulic design) is an important design objective.

- **Hydraulics and Earthwork.** Hydraulic and earthwork design guidance for wetlands is available in Palermo (1992), Miller and Tate (1993), and Richards (1993b). Techniques for detention-pond analysis and design are also applicable to many aspects of hydraulic design for constructed wetlands, but the designer will need to consider factors specific to wetlands (Reed 1990; Palermo 1992).
- **Operation and Maintenance (O&M).** An O&M plan should be developed during design of CPAWS. O&M plans should address operation and cleaning of inlet and outlet structures, biomass harvesting, berm maintenance, and monitoring.
- **Monitoring.** Monitoring is an important element in the operation of CPAWS. Monitoring should focus on treatment effectiveness and effluent quality. Treatment effectiveness should be based on pollutant mass balances and as such will require monitoring inflow, influent pollutant concentrations, outflow, and effluent pollutant concentrations. Vegetation should also be monitored for coverage, health, and diversity.

SIMPLIFIED DESIGN EXAMPLE: The example given here is hypothetical and illustrates a simplistic analysis suitable for initial feasibility evaluation. More detailed analysis would be needed to proceed with planning and design.

Experimental wetland mesocosm studies showed a half-life of 8 days for atrazine (a herbicide) in a fully vegetated wetland. For an atrazine influent concentration of 20 $\mu\text{g}/\ell$ and a target effluent concentration of 3 $\mu\text{g}/\ell$, the calculated HRT is 22 days (see Fig. 3). Assuming an average depth of 3 ft and a design flow of 10 ft^3/sec , the needed wetlands area is about 146 acres. This acreage estimate is suitable for initial assessment of site availability and configuration alternatives.

CONCLUSIONS: The design sequence presented can be used for initial planning and feasibility assessments for nonpoint source pollution abatement using constructed wetlands. Chemical half-life and hydraulic retention time are key design parameters. Hydrologic analysis is essential in designing wetlands for nonpoint source pollution control.

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First Order Process Equation

$$C = C_0 e^{(-kt)}$$

C = concentration, C_0 = influent concentration, k = first order disappearance coefficient, and t = time.

Chemical Half-Life

From mesocosm studies, atrazine half-life is 8 days.

$$t_{.5} = 8 \text{ day}$$

First Order Disappearance Coefficient

By definition $C/C_0 = 0.5$ when $t = t_{.5}$

Rearrangement of the First Order Process Equation yields

$$k = \frac{-1 \cdot \ln(0.5)}{t_{.5}}$$

$$k = 0.087 \cdot \text{day}^{-1}$$

Hydraulic Residence Time (HRT)

The HRT needed to reduce an influent concentration of 20 ug/L to 3 ug/L is obtained by substituting these values and the first order disappearance coefficient into the basic process equation and rearranging as follows:

$$C = 3 \quad C_0 = 20$$

$$t = \frac{\ln\left(\frac{C}{C_0}\right)}{-1 \cdot k}$$

$$t = 21.9 \cdot \text{day}$$

The needed HRT is about 22 days.

Wetland Area Area = [(Flow) (HRT)] / (Depth)

$$\text{Flow: } Q = 10 \frac{\text{ft}^3}{\text{sec}}$$

$$\text{Depth: } D = 3 \cdot \text{ft}$$

$$\text{HRT: } \text{HRT} = 22 \cdot \text{day}$$

$$\text{Area} = Q \cdot \frac{\text{HRT}}{D}$$

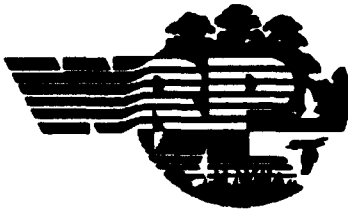
$$\text{Area} = 145.5 \cdot \text{acre}$$

Figure 3. Simplified Design Example

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Procedures For Evaluating Wetlands Non-Market Values and Functions

PURPOSE: This technical note provides a procedural framework for evaluating the economic values of wetlands. Important economic concepts on supply/demand and valuation are presented as they relate to the economic values supported or provided by wetlands. The framework presented here can be used to evaluate economic values within the Section 404 process, while recognizing the difficulties of wetland valuation. Economic values of wetlands have been difficult to evaluate due to uncertainties in the relationship between wetland functions and the production of goods and services. Production of some wetland goods and services is better understood than others. Just as there are changes over time in wetland habitat and other functions, economic values of wetlands change over time and should be accounted in the Section 404 evaluation process.

BACKGROUND: Wetlands perform many functions that provide goods and services to society and have economic value (Shabman and Batie 1988). To be of economic value, there must be a demand for the good or services. However, providing the good or service alone does not result in economic value if there is no demand. Goods or services may be in over-supply or available at no cost. Consequently, only those goods or services for which there is demand have economic value.

The focus of wetland assessment within the context of the Section 404 Program is the determination of the effects of a proposed action on a wetland site. For economic considerations, this focus must be expanded because the economic values associated with a single site are determined, in part, by the affected area's relationship to local, regional or larger economic conditions. To assess the potential for economic value, the relationship and significance of the wetland site's economic services within the larger economic context must be established. Information in this technical note provides the basis for establishing the potential relationship between an affected wetland and the market and other economic conditions that determine its economic value, as previously outlined in an internal working document. Henderson, J.E. 1991. "A Conceptual Plan for Addressing Wetland Economic Values," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

EVALUATION FRAMEWORK: A quantitative dollar and cents evaluation is not possible with, nor the intent of, this framework. Depending on the particular wetland and functions being assessed and other available information, a determination of economic value can be made in some situations. In most cases, this information then will form the basis for more in-depth data collection and analysis. Goods and services provided by wetlands are shown in Figure 1. The relationship between functions and economic goods and services is summarized in Table 1.

Those wetland functions possessing high functional capacities can be related to economic goods and services by examining the relationships in Table 1. Wetland functions are listed in column 1. The value of the function to society, that is, the importance and significance of the function, is briefly described in column 2. After the assessment, those functions with high functional capacities (col. 1) should be examined to determine potential economic value by relating them to the goods and services (col. 3, Table 1). Information on the goods and services as described below can assist in determining

Wastewater Treatment/Water Quality
Flood Control
Fish and Wildlife Habitat
Land Development
Recreation
Water Supply
Educational/Cultural
Food and Fiber Wetland Production Services
Commercial Fisheries, Agriculture, Timber

whether economic values exist. "Supply/demand" information describes how goods and services are provided to society and their relation to local, regional, or larger contexts. Information on "valuation considerations" explain the technical basis for determining economic value. Information about markets and other data that is not a part of the functional assessment will be needed to complete the economic evaluation. Table 2 summarizes the information needs and additional sources.

Figure 1. Economic Goods and Services

- **Wastewater Treatment/Water Quality.** Evaluating the economic benefits for water quality requires determining the value of improved water conditions. These benefits can be determined by establishing relationships between inflow sediment and pollutant characteristics, storage capacity, sediment retention and nutrient transformation capacity. The construction and other costs associated with providing alternative water quality treatment can be used to value the water quality improvement attributable to the wetland.

Key Considerations are areal scale of changes in water quality services; i.e., assessment of whether the changes in water quality at the wetland is significant to the overall water quality of the watershed or basin, or whether the loss of water quality is a localized effect; structural and non-structural water quality measures; and appropriate water quality standards.

Demand/Supply Considerations are magnitude and areal extent of effects on downstream water quality; changes in sediment, nutrient, and other water quality parameters for downstream reaches; contribution and significance of affected wetland to localized water quality.

Valuation Considerations where $\text{Value} = (\text{Cost of using alternative}) - (\text{Costs of using wetland})$. Value of wetland water quality services requires identifying the alternative means (e.g. structures, treatment) and costs to provide the same level of water quality improvement provided by the wetland. Costs of continued use of an unaltered wetland may be negligible, but there may be opportunity costs for not using the wetland for other benefits, e.g. habitat, which may be incompatible with wastewater treatment/water quality services.

- **Flood Control.** Evaluation of flood control benefits requires estimating flood damages with and without the wetland's flood control capacity. These benefits can be determined by establishing the relationships between wetland flood storage capacity and flood damages downstream, and the costs of providing alternative flood control structures or provisions for flood control.

Key Considerations: Existing structures, floodplain measures, and plans for flood control may provide adequate level of flood control; i.e. wetland storage may not be needed (demanded) for flood protection, and may therefore not be of economic value. Wetland storage may be a localized effect, not significant on a watershed or regional scale.

Table 1. Relationship of Wetlands Functions to Economic Goods and Services

Functions	Value of Functions	Economic Goods and Services
Detain, remove, and transform contaminants	Maintain surface and groundwater quality	Wastewater treatment/water quality
Detain and remove sediments	Maintain surface water quality	Wastewater treatment/water quality
Provide ecosystem, landscape and global integrity	Maintain ecosystem, landscape, and global processes	Educational/Cultural Habitat
Provide wetland ecosystem structure	Maintain populations of wetland dependent plants and animals species, preserve endangered species, maintain biodiversity, provide dispersal corridors	Fish and wildlife habitat
Provide a setting for cultural activities	Produce food and fiber, provide recreational opportunities, provide education and research opportunities, provide aesthetic enjoyment, preserve archaeological/historic sites	Commercial fisheries; agriculture, timber, peat production Education/Cultural
Store surface water	Reduce flood-related damage	Flood control
Reduce the energy level of surface water	Reduce erosion from storms and floodwater	Land development
Recharge groundwater	Maintain pumpable supplies of groundwater	Water supply
Discharge groundwater	Maintain stream and lake water levels	Water supply
Stabilize soils	Reduce erosion of shorelines and streambanks from storms and floods	Land development
Detain, remove, and transform nutrients	Maintain surface and groundwater quality	Wastewater treatment/water quality

Table 2. Information Needs

Available from Wetland Functional Assessment	Not Available from Wetland Functional Assessment
<u>Wastewater Treatment/Water Quality</u> Sediment and contaminant retention and transformation capacity Water storage capacity	<u>Wastewater Treatment/Water Quality</u> Regional water quality, wastewater treatment plans Costs of structural alternatives
<u>Flood Control</u> Storage Capacity Downstream land uses and floodplain	<u>Flood Control</u> Areal extent of flood protection provided by wetland Flood damage estimates
<u>Habitat</u> Habitat types affected Threatened and endangered species habitat affected	<u>Habitat</u> Plans and costs for replacement of wetland
<u>Land Development</u> Size, configuration of affected wetland Proximity to roads, infrastructure	<u>Land Development</u> Land market (real estate) transaction data Plans and costs for replacement of wetland
<u>Recreation</u> Areal extent of recreation resource Habitat quality to support consumption, i.e. hunting and fishing Indication of types of possible recreation activities possible	<u>Recreation</u> Supply of regional recreation resources and significance of affected wetland (quantity and quality) for regional resources Recreation user characteristics: Distance traveled and travel costs Age, income, and other demographic distributions Mix of types of recreation use Institutional considerations on demand, e.g. bag and catch limits, hunting and fishing seasons Willingness to pay values
<u>Water Supply</u> Potential of wetland to discharge and recharge groundwater Hydrology and groundwater relationships	<u>Water Supply</u> Existing infrastructure for providing water supply Engineering or other alternatives and costs for water supply
<u>Educational/Cultural</u> Screening for Red Flags Access to the affected wetland Scarcity/Abundance of affected wetland type Vegetation, landform, water components and other factors important for visual quality assessment Public review comments on issues of proposed action	<u>Educational/Cultural</u> Public concerns regarding local and regional wetlands, historic values and aesthetics State and local laws and policies regarding Red Flag issues
<u>Food and Fiber Wetland Production</u> Land uses and patterns Habitat, vegetation, soils and information important for evaluation of production potential	<u>Food and Fiber Wetland Production</u> Regional production patterns Market specific information, e.g. market prices, production costs

Supply/Demand Considerations are areal extent of flood protection provided; importance and value of downstream land uses, e.g. agriculture, residential or urban development; existing flood control or storm surge projects providing flood protection to the same area; existing comprehensive flood control/floodplain protection plans or programs; and possible induced private or public development actions (construction, regulation) if flood storage were reduced.

Valuation Considerations where $\text{Value} = (\text{Value of flood damages without wetland storage}) - (\text{Value of flood damages with wetland storage})$, require determination of aerial extent of flooding with and without the wetland storage and valuation of flood losses under the above with and without conditions.

- **Fish and Wildlife Habitat.** A number of wetland functions support wetland fish and wildlife habitat services that may have economic value as existence, preservation and bequest—the nonuse values; and habitat as input to other economic values of recreation, educational/cultural, and production services—use values considered elsewhere in the text. Little work has been done to estimate the economic benefits of the nonuse values, with most of the effort on quantifying habitat quality.

Key Considerations are scarcity of habitat types and importance/significance of habitat on a landscape, ecosystem, or regional basis; the ability to effectively create substitute wetlands through construction or restoration; and altered wetlands may also provide (or be managed to provide) habitat.

Supply/Demand Considerations are areal extent and significance of affected wetland habitat in local, regional or ecosystem context; habitat quality of affected wetland; importance of affected habitat for species life stages or migration; habitat for threatened or endangered species; availability of replacement habitat; and feasibility, in terms of available technology, and success associated with replacement of the particular habitat type.

Valuation Considerations where $\text{Value} = \text{Costs of a substitute for the habitat services}$. Costs associated with monitoring and maintenance should be included with the engineering and other construction costs. Although there is increasing information on costs of substitutes (necessary for valuation) through creating, constructing, or replacing wetlands, there is uncertainty in the ability of substitute wetlands to successfully or effectively replace the affected functions or habitat. Evaluation should include ability to ensure substitute will actually provide the same habitat.

- **Land Development.** Pressures for changes in land use often result in the conversion of wetlands to agricultural, forestry, urban, and water based residential uses. Agricultural and forestry uses (considered elsewhere in this text) are often a transitional stage in the conversion to urban uses. The aesthetic and waterfront location amenities of wetlands result in extensive pressure to convert wetlands to residential development. Valuation of residential land development is possible because markets exist for residences.

Key Considerations are residential land sale transactions or real estate appraisals can be used to value land development; the services provided by unaltered wetlands, e.g. habitat, educational / cultural, should be considered as well as the services that could be provided by modified development to minimize impacts or losses; and value of wetland characteristics must be isolated from the value of any existing improvements.

Supply/Demand Considerations are availability of non-wetland sites, with similar amenities, for development (in some areas, wetlands may indeed offer the only site for waterfront and other amenities); existence and stability of a functioning local land market; and historic change in prices, i.e. whether or not any dramatic changes in land market has occurred in recent time period indicating increased demand.

Valuation Considerations. Both approaches depend on identifying feasible alternative development plans that reduce the need for wetland conversion. If a non-wetland alternative for development exists, $\text{Value} = (\text{Value of wetland development site}) - (\text{Value of next best alternative})$ and if no development alternative exists, $\text{Value} = (\text{Sale price of developed lot}) - (\text{Cost of developing the lot})$.

Two approaches, hedonic valuation or appraisal methods, may be used. Both are based on the market value of wetland residential development sites; hedonic approach requires enough market transactions to develop a statistical model.

Hedonic valuation studies identify and value different characteristics of wetland development sites and quantify the importance of development site characteristics to the market value of wetland residential sites. Site characteristics important to development are categorized as site amenities, location factors, and historical factors; examples are site amenities, lot size; level of waterfront amenities, such as linear fee of water frontage, whether the lot isolated on a natural bay or a man-made channel; proximity to unaltered wetlands; market value of improvements; location factors, location advantage provided to residence by proximity to shopping centers and other public services; and historical factors, change in general price levels in local or regional real estate markets.

In comparing the value of substitutes, comparability of identified alternatives should ensure the lots are really comparable in terms of the wetland based amenities and are not actually alternative development sites with different types or levels of amenities; consideration of value of improvements to development sites should include only site development and improvement for a building site. Modifications of a land parcel beyond that required to prepare the site to a minimum standard necessary to provide residential housing services should not be included. Extensive wetland site modifications do not contribute to the net development value of a wetland area as they provide services that are not unique to the wetland development.

Appraisal methods use the expected sale price for residential parcels to estimate the value of wetland development. The market comparison appraisal approach uses data from comparable parcels to infer the market value of a lot. Land market sales records, tax records, and local real estate experts can be used to support this method. Establishing comparable sales requires that adequate market data be available. An alternative appraisal method is the replacement cost method which establishes market value for replacement of the physical aspects of the site; that is the cost of building on another equivalent wetland site.

- **Recreation.** Wetland areas support recreation for consumptive, i.e. hunting and fishing, and non-consumptive purposes, e.g. wildlife viewing (considered under Educational/Cultural). Recreation use is determined in part by the biological productivity of the wetland in producing game species, and by available access and size of the recreation area, both of which are available from a regulatory application. Additional determinants of demand are demographic characteristics, e.g. age, income, travel time; experiential aspects, e.g. years of recreation experience, importance of bag or catch to the user, congestion at the recreation site; and institutional constraints on bag or catch limits and season length.

Valuation of recreation for regulatory actions should include identification of types and extent of recreation occurring in the larger region; assessment of the quantity and quality of the recreation resources at the site; identification of possible alternative sites for activities; and estimation of future recreation both with and without the proposed development, with consideration being given to recommending modified development, that is, incorporation of recreation opportunities, e.g. access, in development plans.

Key Considerations. Evaluation requires certain assumptions about the relationship between recreation use and wetland habitat and other resources. These relationships are required to predict changes in recreation use in response to development.

Demand/Supply Considerations. The assessment procedure should determine the magnitude and significance of changes in available recreation resources due to development of the wetland area. There may be substitutes for the range of wetland recreation activities at different sites. Displaced recreation may move to other under-used areas or cause overuse at already congested areas; these conditions should be considered in the evaluation. Supply can be assessed in terms of quantity of recreation resources, e.g. number of acres; quality of the resources, including quality of access. Demand is usually approximated by the complex interactions of wetland resource attributes; user characteristics which act as demand shifters are such things as taste, preferences, income, hunting or fishing success; institutional constraints; and the availability of appropriate substitutes or alternatives. General information on existing recreation use may be available from state or local fisheries and wildlife management agencies.

Valuation Considerations where Value for wetland recreation at a site = (willingness to pay (WTP) to recreate at the wetland site) - (WTP for same activities at next best alternative). This formula requires identifying alternative recreation sites and evaluating WTP values for both the affected wetland and for the substitute.

Accepted valuation methods for WTP are the travel costs method that uses costs of travel and time as proxies for WTP; the contingent valuation method in which users respond to proposed wetland recreation conditions; and the Unit Day Value Method which assigns a standardized value to the quality and other characteristics of recreation resources.

- **Water Supply.** The ability of wetlands to recharge and discharge groundwater can provide water supply services. There are few documented uses of wetlands for water supply due to uncertainty in interactions between wetlands and groundwater and in the capacity to use wetland water supplies without damaging the wetland itself. Better understanding of wetland hydrology and wetland-aquifer interactions may change demand for wetland water supply services. Engineering costs for providing water supply are generally available and can be used to value the costs of alternatives for wetland water supplies.

Key Considerations. Valuation of wetland water supply is dependent on establishing demand or need for the water; relationship between affected wetland area and the local groundwater supply; and valuation of the alternatives or substitutes for the wetland water supply.

Supply/Demand Considerations. In many areas, wetlands serve as secondary, rather than primary, water supply sources. Evaluation requires establishing the extent of potential local or regional demand for the wetland water. Groundwater recharge and discharge capacity and areal and hydrologic measurements can be used to determine potential water supplies, but these must be

compared to the demand for additional water. Local or municipal water supply agencies provide information on existing supply and costs.

Valuation Considerations. Valuation is determined by the availability of alternative water supply. If no alternative exists for the wetland water supply services, Value = value of the water supply to the consumer. If alternatives exist, Value = (costs of development of wetland water supply) - (costs of development of alternative water supply sources).

Evaluating differences in costs between the wetland and an alternative water source entails determining the costs of alternative sources and then comparing those costs to those of the wetland source. Identification of the least cost alternative is not straightforward since little use and costs data for wetland water supplies exist. Engineering and hydraulics personnel can provide development costs for alternative water supply, and public utility records can be used for unit costs of water.

- **Educational/Cultural.** Educational/cultural goods and services provided by wetlands are based on the significance of wetlands for human uses and preservation. Educational/cultural services are composed of natural, scenic, or aesthetic values; historic, archaeologic, or public use values; and non-consumptive recreation values, e.g. bird watching (consumptive recreation is covered in recreation). Monetary valuation is not normally attempted or appropriate. Rather, significance or technical ratings of quality are determined for the components.

Key Considerations. It is often difficult to separate educational/cultural services from the provision of other goods and services, e.g. flood control. These values derive from the existence of the wetland in a natural or undisturbed state, rather than the value derived from some use of the wetland.

Supply/Demand Considerations. Visual quality characteristics and potential for recreation in the affected wetland are evaluated in terms of regional scarcity and quality. The question is "Are the visual and recreational resources unique or scarce, and will there be a significant loss with development?" The visual quality is determined by the relative uniqueness of vegetation, water, land-form, etc, and whether these visual characteristics are unique or abundant in the region. For recreation, wetland size, public access and use, and availability of substitutes in the region must be considered. Historic and cultural resources must be identified and their significance determined, if present. The wetland may be of cultural significance because of its role in providing food, fiber and other necessities for groups engaged in subsistence economies.

Valuation considerations consist primarily of visual quality applications. Wetlands provide visual diversity in upland and especially urban environments. Wetland aesthetics have been evaluated and show variation between regions. Studies have related wetland characteristics to overall visual quality with varying levels of success. Other things being equal, people prefer open water/marshy wetland areas to thickly vegetated shrub/woody swamps where visual access is impaired. Visual quality is related primarily to the shape of the upland wetland edge, the vegetation/water interspersion pattern, and pattern or relation of types of vegetation or vegetation classes. Shape of wetland/upland edge: Irregular, non-straight line edges have higher visual quality. Vegetation/water interspersion pattern: Mosaic patterns of vegetation interspersed among channels, pools, and flat water areas are of higher visual quality than intermediate conditions or well defined vegetation areas with little or no interspersion. Vegetation class interspersion: Mosaics of vegetation types or classes of similar heights are of higher visual quality than well defined areas of single vegetation types with little or no interspersion.

Historic Values: Screening for Red Flags during the evaluation process determines whether or not the affected wetland is protected under Federal policy; applicable State and local screening criteria should be identified. Potential impacts to protected historic or archaeological resources should be evaluated by District personnel.

Non-consumptive Recreation: Non-consumptive recreation potential is determined by physical access to the wetland areas and the abundance and diversity of wetland vegetation, wildlife and other resources necessary for recreation.

- **Food and Fiber Wetland Production Services.** Habitat functions support agriculture, forestry, and commercial fishery production. Economic valuation is determined by market conditions, and production functions that incorporate production factors and supply and demand considerations.

Key Considerations. For commercial fisheries, linkage must be established between habitat availability, habitat productivity; production costs, e.g. harvest; and changes in the wetland. Little data is available on valuation of wetland forest management or conversion to intensive silviculture. Decisions on agricultural production, on the other hand, are complicated by provisions of the Food Security Act (Swampbuster).

Supply/Demand Considerations. Alternatives or substitutes for production services should be identified to determine in value in the differences between wetland production and the next best alternative. Commercial fishery market prices and costs of production are obtainable. Timber production in a wetland or wetland conversion for timber is responsive to the local and regional timber market and future changes in those markets.

Valuation Considerations. Commercial fisheries, agriculture, and forestry are market based so valuation of a wetland is dependent on regional markets. Valuation must consider whether the service can be produced elsewhere, i.e., whether there is a production alternative. The value of the wetland production services is measured as the change to the economic surplus, i.e., return of the wetland to private owner. Value of wetland for production: (Net returns from production from wetland harvest) - (Net returns from production from next best alternative).

Fisheries. Valuation of wetland fisheries is determined by production models relating changes in catch to changes in production factors, e.g., habitat size, water quality, level of harvest effort. Changes in catch can then be multiplied by the market price of the fish. Difficulties in this approach, known as marginal value product method, are in formulating a production function.

Agriculture. Decisions to convert wetlands to agricultural production must account for the profitability of different crops given the market for respective crops; government price supports and targets; availability of suitable non-wetland rental lands; and the Swampbuster provisions of the Food Security Act (making farmers ineligible for government supports if crops are grown on converted wetlands). Value is measured by the projected change in return to the farmer.

Forestry. Value for timber production is the stumpage value, i.e. the value of the timber that can be cut off the site, if there is no alternative for timber production. If alternative sites exist, then value is the difference between the returns to development and returns to development of the next best alternative.

CONCLUSIONS: The economic evaluation framework presented in this technical note uses and builds on information obtained when assessing wetland functions and their relationships to economic

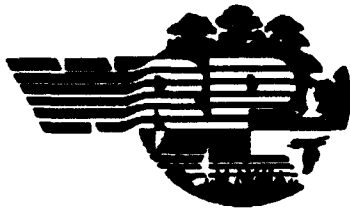
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goods and services. For those wetland functions assessed as having a high functional capacity, a method is to determine whether or not there is potential for economic value is outlined.

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Methods for Evaluating Wetland Functions

PURPOSE: The purpose of this technical note is to review the major wetland evaluation methods currently in use among wetland professionals and to provide a comprehensive list of these methods for use by field biologists and managers. Method selection can be based on study objectives; amount of time, budget and personnel available; regional or local controversy; and degree of precision and accuracy required.

REVIEW PROCESS: A total of 17 methods were reviewed. These methods are widely used and have applicability to the Section 404 review process. The analysis compared the similarities and differences between the variables used to assess wetland functions. Four of the methods reviewed are designed for generalized use: the Habitat Evaluation Procedures (HEP), Habitat Assessment Technique (HAT), Wetland Evaluation Technique (WET), and Ontario Method. These four, and other methods which are more region specific, are listed in Table 1 by author and by their commonly accepted names.

We grouped wetland functions into four broad categories: hydrology/water quality; landscape integrity; fish and wildlife/habitat; and recreation/aesthetic. Each method was reviewed to determine if it addressed the major functional categories and the types of variables used to measure the functions (Table 1.) Three previous reviews of methods addressing different issues may be of use to supplement this review.¹

No consensus was evident on the numbers of variables used to evaluate wetland functions. The WET addresses the greatest number of variables (94), and HAT, the fewest (3). Collectively, the 17 methods address 300 variables (Table 1). However, the number of variables that three or more methods have in common was 78: hydrology/water quality (16), landscape integrity (31), fish and wildlife/habitat (13), and recreation/aesthetic (18). This smaller list has been compiled into Table 2 and may be useful to evaluators and reviewers of permits to reduce the number of variables included in the analysis. Generally, a greater number of variables will increase time and cost of the analysis. Conversely, too few variables may not provide enough information for sound decision making.

- **Hydrology/water quality.** Fifteen of the methods included variables related to hydrology/water quality (Table 1). Of these methods, three used three or less variables to evaluate this category. The most comprehensive series of variables was contained in WET with 28, although several methods used 12 or more variables.
- **Landscape Integrity.** All of the methods included one or more variables to evaluate landscape integrity. Four methods evaluated this category with four or fewer variables (Table 1). The greatest number of variables was included in HEP with 35.

¹ See Lonard et al. (1981), Kusler and Riexinger (1986), and Adamus (1989) in the suggested-reading section.

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- **Fish and Wildlife/habitat.** Thirteen methods included one or more variables to evaluate fish and wildlife/habitat (Table 1). HEP used the greatest number of variables at 27. Six used four or less variables to evaluate this category.
- **Recreation/aesthetic.** Thirteen methods included one or more variables to evaluate the recreation/aesthetics category (Table 1). Six used four or less variables. The Wetland Evaluation Guide used the most comprehensive list of variables at 47.

RECOMMENDED ADDITIONAL READING:

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Table 1
Variables Used for Wetland Evaluation

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hydrology/Water Quality																	
Abundance of cover in stream/river										X						X	
Alkalinity												X					
Bacterial concentration			X									X					
Bank stabilization																	X
Bottom water temperature										X		X					
Climate regulation	X											X					
Condition of shoreline													X				
Constriction of wetland												X					
Contribute to groundwater quality	X	X	X				X					X				X	
Contribute to groundwater quantity							X										
Contribute to surface water quality	X	X	X						X			X					
Contribute to usable surface water	X																
Dispersal of toxics	X																
Dominant flooding regime												X					
Downstream sensitivity													X				
Erosion control	X	X		X					X				X	X			
Flood damage potential downstream													X				
Flood flow alteration			X									X					
Flood peak flows													X				
Flood protection/control	X			X					X							X	
Flood tolerance index																	
Flood water desynchron. and stor.		X														X	
Flooding extension and duration											X	X	X				
1 Witty et al., Wetland Eval. Guide. 2 Gosselink, Le, Cum. Ass. of BLH. 3 Cooper et al., Intermount Riparian. 4 Anchorage Assess. 5 Golet, Freshwater NE. 6 Smardon, Fabos, Vis./cultural Model 7 Heeley, Motts, Groundwater Restor. 8 Cable et al., HAT. 9 Marble, Gross, Assess. Wet. Chairs. 10 USFWS, HEP. 11 O'Neil et al., BLH. 12 Adamus, WET II. 13 CORPS, WEM. 14 Euler et al., Ontario Method. 15 Hollands, McGee, H&M. 16 Ammann, Stone, NH/CONN Meth. 17 North Carolina Meth.																	
(Sheet 1 of 11)																	

Table 1 (Continued)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hydrology/Water Quality (Continued)																	
Flooding frequency													X				
Flow augmentation	X	X										X		X			
Flow retention				X													
Flow stabilization				X										X			
Flow variation			X														
Flow, gradient, deposition												X	X				
Groundwater discharge			X									X					
Groundwater recharge	X		X									X					
Growing degree-days														X			
Heavy metal concentration			X							X							
Hydrologic connection															X		
Hydrologic position															X		
Living filter																	
Measure of D.O.			X							X		X	X				
Nutrient levels	X	X	X	X						X			X	X			
Nutrient removal												X		X			X
Nutrient retention		X										X				X	
Physical char. of stream channel										X						X	
Poorly drained soils-% of wetland																X	
Precipitation rate												X					
Presence of inlets/outlets												X			X		
Presence of springs													X				
Pres./abs. of temp. pools of water										X							
Production exports (organics)			X									X			X		
Recharge to regional aquifer	X		X														
Reduction of tidal impacts	X																
Salinity and conductivity of water										X		X					
Sediment flow stabilization	X		X									X					
Sediment removal																	X

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Table 1 (Continued)																	
Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hydrology/Water Quality (Continued)																	
Sediment trapping		X	X						X			X	X			X	
Shoreline anchoring													X				X
Slope of watershed above wetland																X	
Storage of agriculture runoff	X																
Storage/recycling of human waste	X																
Streambank shade			X							X						X	
Surface drainage																	X
Surface substrate type												X					
Surface water persistence				X											X		
Suspended solids										X		X					
Toxicant removal																	X
Toxicant retention												X					
Transmissivity of aquifer															X		
Underlying glacial material							X										
Water catchment	X																
Water chemistry					X												
Water conveyance																	X
Water depth										X		X	X		X		
Water detention		X												X			
Water level fluctuation										X					X		
Water quality										X						X	
Water storage																	X
Water temperature										X		X					
Watershed protection	X								X								
Wetland hydroperiod																X	
Wetland outlet restriction																X	
Adjacent to tributary of Great Lakes													X	X			
Buffer zone for natural area										X							X
Contiguity among patches		X								X							X
(Sheet 3 of 11)																	

Table 1 (Continued)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Landscape																	
Contiguity to stream/lake		X		X		X							X		X	X	
Contiguity to upland		X										X				X	X
Cover type					X					X		X	X				
Diameter of canopy layer trees										X	X	X					
Diameter/number/condition of snags										X		X					
Dominant wetland class					X								X		X	X	
Ecological age of wetland														X			
Edge bordered by a buffer-%										X						X	
Edge bordered by upland hbtt.-%										X						X	
Edge effect of commun. types				X		X					X	X		X			
Existing disturbance										X		X					
Fetch and exposure												X		X	X		
Fraction of type remaining		X															
Fringe wetland												X					
Gradient												X	X				
Ground cover-%										X	X						
Habitat diversity			X	X						X			X			X	
Internal wetland contrast						X						X		X			
Interspersion of shade												X				X	
Interspersion type					X				X	X	X	X			X	X	
Is area an island?												X					
Landform contrast																X	
Local topography											X	X			X		
Located at extreme limit of range													X				
Location and size of detention areas														X			
Long term stability																X	
Maintainance of biological diversity	X																
Open space or corridors										X			X				

(Sheet 4 of 11)

Table 1 (Continued)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Landscape (Continued)																	
Open water types				X						X		X		X			
Open water-%															X	X	
Patch size distribution		X															
Position within watershed				X					X			X			X		X
Presence of fen or bog													X	X			
Presence of native prairie												X	X				
Presence of swamp or marsh														X			
Protection of natural shorelines	X																
Proximity to large water bodies										X		X					
Proximity to other wetlands				X	X	X				X		X	X	X	X	X	
Restoration potential/value																	X
Scarcity of type						X						X		X			X
Sensitivity to disturbance				X							X	X					X
Shrub cover-%											X					X	
Size of adjoining lakes and rivers														X			
Size of watershed	X									X		X				X	
Size of wetland		X	X	X	X	X		X	X	X		X		X	X	X	
Soils type				X						X		X		X			
Spatial diversity			X							X							
Stand maturity										X	X						
Stream corridor vegetation																X	
Subclass richness					X								X		X		
Surface substrate										X	X						
Surficial geology							X					X			X		
Surrounding habitat types					X					X				X	X		
Tree canopy closure										X	X						
Vegetation class interspersation										X		X	X				
Vegetation community structure				X						X	X						
Vegetation cover-%										X	X	X	X				X

(Sheet 5 of 11)

Table 1 (Continued)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Landscape (Continued)																	
Vegetation density										X	X				X	X	
Vegetation diversity			X			X				X		X					
Vegetation type										X		X	X	X			
Vegetation-water interspersions										X		X				X	
Vegetative species richness										X					X		
Vegetative width										X		X					
Waterbody diversity						X										X	
Watershed position			X														
Water/cover ratio															X		
Wetland bordering open water-%										X					X		
Wetland class richness					X								X		X	X	
Wetland morphology																X	
Wetland type	X			X	X	X						X	X	X			
Wetland types within a wetland-#										X				X			
Width of wetland										X			X			X	
Wildlife access to other wetlands																X	
Wildlife/Habitat																	
Abund. of aquatic insects/inverts			X							X		X					
Biological control	X																
Bird species richness		X								X							
Breeding bird diversity				X						X							
Breed. hbtt. for endan. plants/ anim.														X			
Breed./feed. hbtt. for signif. species														X			
Dominance of robust emergents				X						X			X	X			
Identifiable guilds			X														
Mast production by trees										X	X						
Migration habitat	X			X								X					

(Sheet 6 of 11)

Table 1 (Continued)																	
Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Wildlife/Habitat (Continued)																	
Migration or feed. hbtt. for T&E spp.														X			
Nursery habitat	X																
Plant productivity												X					
Presence of coldwater fish species													X				
Presence/absence of indicator spp.		X								X							
Proportion of wildlife food plants										X					X		
Quality of spawning substrate										X			X				
Quality habitat for plants and animals	X									X							
Rare/threat. endan. plants/animals	X	X		X								X	X	X	X	X	X
Scarcity of spawning habitat										X			X				
Significant habitat for aquatic life										X							X
Significant habitat for birds				X						X		X					
Significant habitat for crustaceans	X									X							
Significant habitat for fish		X	X	X						X		X					
Significant habitat for mammals	X									X							
Significant habitat for sport fish	X									X		X					
Significant habitat for wildlife	X	X	X							X		X					X
Significant waterfowl habitat	X									X		X	X	X			
Sig. habitat for reptiles/amphibians	X									X							
Sig. hbtt. for fish spawning/rearing										X			X	X		X	
Sig. nest. hbtt-colonial waterbirds										X				X			
Species diversity								X		X		X					
Submerged or emergent vegetat.-%										X						X	
Total area of pond or lake										X						X	
Unique fisheries															X		
(Sheet 7 of 11)																	

Table 1 (Continued)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Wildlife/Habitat (Continued)																	
Uniqueness of species								X				X					
Unusual abundance of plants/animals	X											X					
Water dependent terr. organisms		X										X					
Waterbird migration populations	X			X										X			
Wetland depend. aquatic organisms		X															
Wetland plant communities-#				X						X							
Winter cover provided										X				X			
Winter fish kills													X				
Wintering habitat										X		X	X	X			
Recreation/Aesthetics																	
Absence of human disturbance										X				X			
Access to navigable waters													X		X	X	
Access to stream/pond/lake																X	
Add to visual diversity of area	X															X	
Adjacent development										X			X				
Adjacent to public lands													X				
Aesthetic quality																X	
Aids groundwater recharge regulation													X				
Ambient quality							X										
Amount of original wetland filled-%																X	
Archaeol./paleon. resources	X											X				X	
Area dominated by flowering trees-%																X	
Audio qualities	X									X							
Barriers to anadrom. fish (ie dams)																X	
Boating opportunities	X													X			
Commercial harvest (hunt, trap, fish)	X											X		X			
<i>(Sheet 8 of 11)</i>																	

Table 1 (Continued)																	
Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Recreation/Aesthetics (Continued)																	
Commercial uses (rice, peat)	X													X			
Contribute to local/regional economy	X													X			
Contribute to urban flood protection	X																
Direct alteration												X					
Distance from urban population	X											X		X			
Distance to education facility	X			X								X		X		X	
Distance to roads										X		X	X				
Dominant land use																X	
Dominant land use above wetland																X	
Ease of access	X			X			X						X	X	X	X	
Economic value																	X
Educational use	X			X		X						X	X	X			X
Enhance crop production	X													X			
Enhance development values	X																
Enhance urban water quality	X																
Existing alterations													X				
Fisheries management area																	
General appearance of wetland																X	
Handicap access																X	
Hazards limiting public use																X	
Historical area/buildings																X	
Important sightseeing locale	X												X				
Interpretive program	X			X										X			
Land use along river/stream														X			
Land use in watershed														X			
Land use patterns (general)													X				
Landscape distinctness														X			

(Sheet 9 of 11)

Table 1 (Continued)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Recreation/Aesthetics (Continued)																	
Level of human activity in upland																X	
Level of human activity in wetland									X							X	
Local significance																X	
Location (public/private land)	X			X								X	X	X	X		
National natural landmark																X	
Noise level at viewing locales																X	
Number of visitors	X																
Occupied buildings along edge-#																X	
Occurrence of mineral, gas, oil	X																
Odors present at viewing locales																X	
Offroad parking for buses/cars																X	
Open space function	X			X									X				
Opportunity for noncommercial use	X																
Part in pattern of settlement	X																
Part of heritage of region	X											X	X				
Photographic opportunity	X																
Plant alteration (ie. mowing)-%																X	
Policies/programs to conserve area	X											X					
Pollution													X				
Presence of harvestable resources	X											X					
Presence of mill pond																X	
Pres. of nature pres. or wild. mgmt.																X	
Project benefits	X																
Proximity to tribal lands													X				
Proximity to wild and scenic river													X				
Public roads/railroad crossings-#																X	
Recreation diversity			X														

(Sheet 10 of 11)

Table 1 (Concluded)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Recreation/Aesthetics (Continued)																	
Recreation experience (general)			X									X					X
Regulated by state or COE													X				
Scarcity of type						X							X		X		
Site of special public interest	X											X					
Source of forage	X																
Source of water for crop irrigation	X															X	
Source of water for livestock	X																
Source of waterfowl for consumption	X													X			
Sport hunting/fishing	X	X												X		X	
Student safety																X	
Tactile quality	X																
Tourism or recreation attraction	X																
Traditional use area	X																
Unique regional resource	X											X	X				
Unusual geol. or structural features														X		X	
Use for domestic water supply	X											X				X	
Use for scientific research	X			X		X						X	X	X		X	
Use for sewage treatment	X											X					
Use of water for industry	X																
Utilized for cultural events	X																
Visibility from highway	X																
Visibility of open water																X	
Visual diversity													X				
Visual dominance	X					X											
Watchable wildlife	X															X	
Wells that serve public												X				X	
Winter recreation	X													X			

(Sheet 11 of 11)

Table 2
Variables Used for Wetland Evaluation Appearing Three or More Times in the Literature

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hydrology/Water Quality																	
Contribute to groundwater quality	X	X	X				X					X				X	
Contribute to surface water quality	X	X	X						X			X		X			
Erosion control	X	X		X					X							X	
Flood protection/control	X			X							X	X	X				
Flooding extension and duration												X		X			
Flow augmentation	X	X										X					
Groundwater recharge	X		X							X		X	X				
Measure of D.O.			X							X			X	X			
Nutrient levels		X	X	X	X							X		X			X
Nutrient removal												X				X	
Nutrient retention			X									X			X		
Production exports (organics)				X								X					
Sediment flow stabilization		X		X						X		X	X			X	
Sediment trapping			X	X							X					X	
Streambank shade				X							X		X	X		X	
Water depth																	
Landscape																	
Contiguity among patches			X								X			X		X	X
Contiguity to stream/lake			X		X		X						X			X	X
Contiguity to upland			X								X		X	X			
Cover type											X	X	X				
Diameter of canopy layer trees							X							X		X	X
Dominant wetland class												X	X		X		
Edge effect of commun. types						X		X									

- 1 Witty et al., Wetland Eval. Guide.
- 2 Gosselink, Le, Cum. Ass. of BLH.
- 3 Cooper et al., Intermount Riparian.
- 4 Anchorage Assess.
- 5 Golet, Freshwater NE.
- 6 Smardon, Fabos, Vis./cultural Model

- 7 Heeley, Motts, Groundwater Restor.
- 8 Cable et al., HAT.
- 9 Marble, Gross, Assess. Wet. Chairs.
- 10 USFWS, HEP.
- 11 O'Neil et al., BLH.
- 12 Adamus, WET II.

- 13 CORPS, WEM.
- 14 Euler et al., Ontario Method.
- 15 Hollands, McGee, H&M.
- 16 Ammann, Stone, NH/CONN Meth.
- 17 North Carolina Meth.

(Sheet 1 of 3)

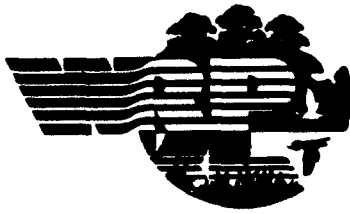
Table 2 (Continued)																	
Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Landscape (Continued)																	
Fetch and exposure												X		X	X		
Habitat diversity			X	X						X			X			X	
Internal wetland contrast						X						X		X			
Interspersion type					X				X	X	X	X			X	X	
Local topography											X	X			X		
Open water types				X						X		X		X			
Position within watershed				X					X			X			X		X
Proximity to other wetlands				X	X	X				X		X	X	X	X	X	
Scarcity of type						X						X		X			X
Sensitivity to disturbance				X							X	X					X
Size of watershed	X									X		X				X	
Size of wetland		X	X	X	X	X		X	X	X		X		X	X	X	
Soils type				X						X		X		X			
Subclass richness					X								X		X		
Surficial geology							X					X			X		
Surrounding habitat types					X					X				X	X		
Vegetation class interspersion										X		X	X				
Vegetation community structure				X						X	X						
Vegetation cover-%										X	X	X	X				X
Vegetation diversity			X			X				X		X					
Vegetation type										X		X	X	X			
Wetland class richness					X								X		X	X	
Wetland type	X			X	X	X						X	X	X			
Width of wetland										X			X			X	
Wildlife/Habitat																	
Abund. of aquatic insects/inverts			X							X		X					
Dominance of robust emergents				X						X			X	X			
Migration habitat	X			X								X					
(Sheet 2 of 3)																	

(Sheet 2 of 3)

Table 2 (Concluded)

Variables	Methodologies																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Wildlife/Habitat (Continued)																	
Rare/threat. endan. plants/animals	X	X		X								X	X	X	X	X	X
Significant habitat for birds				X						X		X					
Significant habitat for fish		X	X	X						X		X					
Significant habitat for sport fish	X									X		X					
Significant habitat for wildlife	X	X	X							X		X					X
Significant waterfowl habitat	X									X		X	X	X			
Sig. hbtt. for fish spawning/rearing										X			X	X		X	
Species diversity								X		X		X					
Waterbird migration populations	X			X								X		X			
Wintering habitat										X		X	X	X			
Recreation/Aesthetics																	
Access to navigable waters													X		X	X	
Archaeol./paleon. resources	X											X				X	
Commercial harvest (hunt, trap, fish)	X											X		X			
Distance from urban population	X											X		X			
Distance to education facility	X			X								X		X		X	
Distance to roads										X		X	X				
Ease of access	X			X			X						X	X	X	X	
Educational use	X			X		X						X	X	X			X
Interpretive program	X			X										X			
Location (public/private land)	X			X								X	X	X	X		
Open space function	X			X									X				
Part of heritage of region	X											X	X				
Recreation experience (general)			X									X					X
Scarcity of type						X							X		X		
Sport hunting/fishing	X	X												X		X	
Unique regional resource	X											X	X				
Use for domestic water supply	X											X				X	
Use for scientific research	X			X		X						X	X	X		X	

(Sheet 3 of 3)



Remotely Sensed Data: Information for Monitoring Dynamic Wetland Systems

PURPOSE: Digital imagery (or digital data) acquired by commercial remote sensing satellites, combined with inexpensive PC-based image processing software provides an efficient and cost-effective capability/technique for monitoring changes to wetland systems. This paper describes some of the potential of this imagery as well as some of the limitations and difficulties inherent in the use of remotely sensed data. Differences between the types of imagery available are described as well as the types of techniques which may be employed to analyze/manipulate the imagery. An example application of the use of this imagery for routine change detection is described.

BACKGROUND: Since the 1972 launch of the first Landsat satellite, the earth's surface has been routinely monitored by sensors specifically designed to study the earth's natural resources. There have now been five Landsat satellites placed successfully in orbit, providing a nearly continuous archive of imagery over the United States. In 1986, the Landsat satellites were joined by the French SPOT series of satellites in their earth observing mission. As satellite imagery represents an effective way of studying large areas of the earth's surface, a great deal of attention has been directed toward using this imagery to map or monitor wetland systems. The Corps of Engineers Wetlands Research Program has published a bibliography of these efforts classifying them by wetland and sensor type (Lampman, 1992).

The use of digital imagery from space platforms has mainly been limited to research laboratories and universities due to the large amount of disk space required to handle the data, the cost of the hardware and software to manipulate the imagery, and the CPU-intensive nature of the algorithms required to extract information from the raw data. These limitations have, for the most part, been overcome by rapid advances in processor speed and the reduction in prices of computer equipment and image analysis software. A computer based on an Intel 80486 CPU, with a disk capacity of 500 megabytes or more and a tape drive or CD-ROM player is all that is required to load, display, and manipulate satellite imagery. Of course, the types of analyses conducted will depend on the software used and the level of expertise of the analyst.

Recently inexpensive software tools have become available which allow users with minimal experience in image processing techniques to load and display satellite imagery and to analyze these data in concert with data stored in a geographic information system (GIS) database. Nearly all the GIS software vendors now offer "query" software which allows users to load imagery, overlay GIS information which has been input in a full-blown GIS, and to output color hardcopy products. Also, imagery vendors have begun to provide an array of products from the raw imagery which make the data easier to use. For example, both EOSAT and SPOT have for some time provided imagery which has been geocorrected (or georeferenced) to a map projection (such as the Universal Transverse Mercator projection). This means that the data can immediately be incorporated into a GIS database and the user is relieved of this laborious task. SPOT Image Corporation has also developed a suite of products which reduce the amount and complexity of processing required of the end user and which help limit the amount of data which must be purchased to meet the needs of a project. For example, SPOT will provide data to match standard USGS map frames, including a 7.5×7.5 minute (Latitude/Longitude), 15×15 minute, or 30×30 minute map sheet, in any projection. Users can also opt to buy imagery by the square mile (for a project boundary) or by linear mile along a corridor

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(such as a river channel, highway, etc.) This means that users only have to purchase the imagery required for their specific application, and it is delivered in a format which can immediately be loaded into a GIS or "query" system. EOSAT also offers a number of options for purchasing less than a full image, including half and quarter scenes.

In the past, satellite data were usually furnished on large 9-track tapes. Nine-track tape drives are extremely expensive items, often costing more than the computers to which they are attached. Today, both SPOT and EOSAT offer data on 8mm tapes, and SPOT has recently begun distributing products on CD-ROM.

TYPES OF DATA AVAILABLE: This technical note only addresses data which are available from the Landsat and SPOT satellites. These satellites carry passive sensors which image the earth in the visible and infrared portions of the spectrum.

When discussing digital image data there are two types of resolution which must be considered: spatial and spectral. Spatial resolution deals with the size of each picture element (or pixel) in the image. The coarser the spatial resolution, the less detail will be visible in the imagery. Spectral resolution deals with the number and width of the portions of the spectrum imaged by the sensor. Most remote sensing instruments divide the spectrum into a number of sections and measure the radiation within each of these "bandwidths." By combining three of these sets of measurements it is possible to produce a true or false-color composite image. Multiple bands of image data are also useful for conducting statistical analyses using image processing software. Table 1 below lists the instruments that have flown on the Landsat and SPOT satellites and their respective characteristics.

Satellite	Sensor	Date	Spatial Resolution	Spectral Resolution
Landsat 1-5	MSS (Multispectral Scanner)	1972-Present	80 x 80 meters	4 channels (visible and near-infrared)
Landsat 4-5	TM (Thematic Mapper)	1982-Present	30 x 30 meters	7 channels (visible, near and middle infrared, and thermal)
SPOT 1-3	Panchromatic	1986-Present	10 x 10 meters	1 channel (visible)
	HRV	1986-Present	20 x 20 meters	3 channels (visible, near-infrared)

TYPES OF ANALYSES WHICH CAN BE CONDUCTED: The types of analyses which can be conducted on imagery are many; essentially, they can be grouped into two types: manual interpretation (sometimes referred to as photointerpretation) or quantitative analysis. The types of analyses which are to be conducted on imagery will depend both on the capability of the software and the knowledge of the analyst. In short, information may either be extracted by manual methods or through extensive digital/image processing.

Often, a great deal of information can be gathered simply by analyzing imagery on a computer screen. For example, one can tell instantly whether or not an area has been cleared by simply "viewing" the data in black&white or as a false-color composite. For this simple type of application spatial resolution is much more important than spectral resolution and SPOT panchromatic data are probably the best choice. However, when using satellite imagery to produce a characterization of

land-cover in an area, multispectral data are required and Landsat TM may be more useful (even though the spatial resolution is only 30 meters as compared to 10 meters for SPOT panchromatic data). Therefore, it is important to consider how the data will be used and what is to be extracted from the imagery.

Multispectral classification of satellite data makes use of the fact that different surface cover types reflect the sun's radiation differently within each of the portions of the spectrum which the sensors image. By analyzing the unique "signatures" of cover types with statistical analysis algorithms, it is possible to produce a land cover classification of an area. This type of analysis requires a good deal more knowledge by the analyst, as well as much more sophisticated (and expensive) software. Work under the Wetlands Research Program has shown that it is very difficult, if not impossible, to map wetlands with imagery alone, particularly when dealing with bottomland hardwood wetlands. However, land cover classifications of satellite imagery can be useful for analyzing changes in adjacent uplands. Multidate imagery (i.e. data acquired at different times) can improve the ability to discriminate between wetland cover types but it is often difficult to obtain imagery at the correct times of the year and processing of more than one data set increases the cost.

The true value of satellite imagery is recognized when the data are used in conjunction with other forms of geographic data in a GIS. Imagery data are easily integrated with GIS systems. For example, it is possible to store information related to the hydric properties of soils, National Wetlands Inventory (NWI) data, wetlands permit data and analyze these data with satellite imagery used as a backdrop. By analyzing multiple dates of satellite imagery it is possible to identify recently developed or cleared areas near potential wetlands. By overlaying hydric soils and the NWI data, it is possible to further determine the likelihood that the suspect areas were originally wetlands. The user can then overlay wetlands permit information and determine whether or not a permit was issued for development. The satellite imagery can be analyzed in a black&white mode or, if the data are multispectral, a false-color composite can be generated. This example use of satellite imagery is one which involves relatively little processing of the imagery by the end user, and can be accomplished with minimally priced software (\approx \$300.00). The main effort involved in such applications is related to developing the digital databases and in purchasing the imagery data.

LIMITATIONS OF IMAGERY DATA: Although imagery data can be extremely useful for change detection and monitoring efforts, satellite data can also present a number of challenges. For example, it is often difficult to obtain an image over the area of interest during the desired timeframe. The revisit characteristics of the satellites, as well as the presence of cloud cover, can limit the availability of data. When change detection is being conducted, this is less of a problem as data from the archive is useful. However, the limitation is critical when data are required in a very specific timeframe; for example, when imagery must coincide with field data collection.

Other limitations arise from the spectral and spatial resolution of the data. The limited spatial resolution of Landsat TM and MSS data sometimes presents problems when the features studied are rather small (or narrow). Riparian wetlands often represent this type of problem. In change detection studies, it may also be difficult to detect minor intrusions into a wetland area ("nibbling"). The spectral resolution of satellite imagery often limits the ability to accurately detect more than a few wetland types and classes. However, some of these limitations are removed when the data are used with ancillary data in a GIS database. Recently the Federal Geographic Data Committee (FGDC) published a report addressing the application of satellite data for wetlands mapping and monitoring (FGDC Wetlands Subcommittee, 1992). This report outlines a number of benefits and limitations of satellite data as well as the experiences of a number of Federal agencies and other organizations in applying these data for wetland studies.

AN EXAMPLE OF A CHANGE DETECTION APPLICATION: The WES Environmental Laboratory has been involved in a major effort to characterize changes to the wetlands in the Cache River basin in Arkansas. As a part of this study, remote sensing data (Landsat) were acquired for multiple dates and these data were evaluated for monitoring the wetlands over the entire basin ($\approx 6 \text{ km} \times 20 \text{ km}$). Visual analysis techniques were employed as well as quantitative multispectral classification. It was often difficult to obtain data at the optimum date for classification, and frequently the best date for analyzing forest classes didn't coincide with the best date for analyzing agricultural patterns, marsh plant cover, etc. This meant that multiple dates of imagery were required to get the best results. Also, without the aid of soils information, a digital elevation model, and hydrography data it was difficult to consistently differentiate uplands forest areas from bottomland hardwood wetlands.

Some of the most exciting uses of imagery data were from simply analyzing the data in conjunction with the other in the contained data GIS. Areas of clearing, for example, were immediately identified. Figure 1 represents a portion of the NWI data for the Cache River basin. The large dark feature along the eastern portion of the basin is classified as a palustrine-forested wetland. However, in Figure 2, which is a black&white portrayal of a false-color composite, it is apparent that most of the area has been cleared. By analyzing previously acquired imagery of the area it was apparent that the area had been cleared between the time the aerial photography which was used to compile the NWI map was obtained and the time the satellite imagery data were obtained. The query software which was used to manipulate these data provided the ability to quickly overlay soils data to determine whether or not the soils in the area were hydric in nature and to display the hydrology of the area. By analyzing the basin in this manner it was possible to isolate errors both in the landcover classifications derived from the satellite imagery as well as in the NWI data. This type of quick, simple access to spatial data and the ability to get repeated, inexpensive snapshots of an area in the form of satellite imagery represents a powerful analysis and site monitoring tool.



Figure 1. NWI data showing palustrine-forested wetland

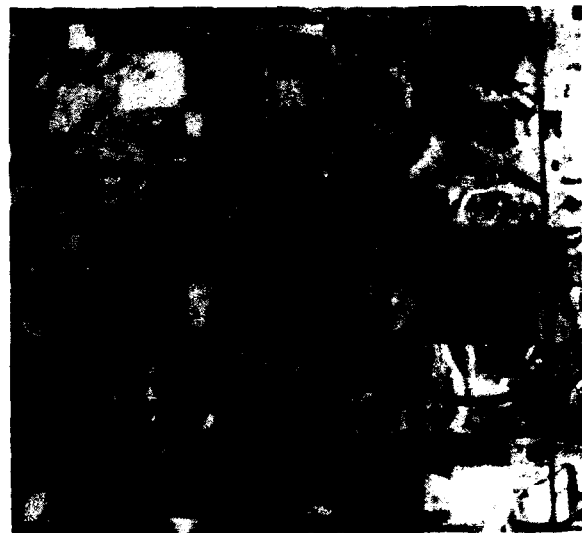


Figure 2. Black and white image of false-color composite showing cleared forested area

RESULTS: Satellite imagery data together with image processing techniques represent a unique tool for monitoring wetlands. Recent developments in terms of software, hardware, and the availability of derived products have removed many of the limitations associated with effectively using remotely sensed data. Users should be cautious, however, when selecting imagery to be used for a specific application, carefully taking into account such things as the optimum date to analyze the features of interest, and the spatial and spectral characteristics of the sensors.

SOURCES FOR MORE INFORMATION: Both SPOT Image and EOSAT produce newsletters which describe the products offered as well as outline some of the applications of these data. Subscriptions to these newsletters are available free of cost and may be obtained by calling the telephone numbers listed below.

ADDRESSES AND PHONE NUMBERS OF IMAGERY SUPPLIERS:

EOSAT
4300 Forbes Boulevard
Lanham, MD 20706
(800)344-9933

SPOT Image Corporation
1897 Preston White Drive
Reston, VA 22091-4368
(703)715-3100

FOR MORE INFORMATION CONCERNING REMOTE SENSING APPLICATIONS WITHIN THE CORPS: The Corps of Engineers has established a Remote Sensing/GIS Support Center to assist Corps district offices in the application of remote sensing technologies. The address is:

U.S. Army Cold Regions Research & Engineering Center
ATTN: Remote Sensing/GIS Support Center (CECRL-RSGISC)
72 Lyme Road
Hanover, NH 03755-1290
(603) 646-4372

REFERENCES:

Lampman, J. L. 1992. "Bibliography of remote sensing techniques used in wetlands research," Technical Report WRP-SM-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

FGDC Wetlands Subcommittee. 1992. "Application of satellite data for mapping and monitoring wetlands: Fact finding report," Technical Report 1, Federal Geographic Data Committee, Reston, VA.

POINT OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Mark R. Graves, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-EN-C, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601)634-2557, author.



Differential Global Positioning System Techniques For Surveying/ Mapping within Forested Wetlands

PURPOSE: This technical note describes the use of Differential Global Positioning System (DGPS) techniques to locate sampling sites and to delineate sampling transects within bottomland hardwood (BLH) forested wetlands. DGPS positioning techniques provide biologists and field scientists with coordinate positions of sample sites throughout the world. A common misconception is that GPS will not provide positions inside a forested area (i.e. BLH). This technical note describes techniques used by scientists at the U.S. Army Engineer Waterways Experiment Station (WES) to provide reliable XY coordinate positions within a BLH forested wetland.

SURVEY TECHNIQUES: The Global Positioning System data collection techniques used for locating XY coordinate positions and mapping transect lines and boundaries within a BLH forested environment were primarily the same as those used outside the forested environment, with the exception of a few tailored operational and data processing steps. Some GPS radio signals do penetrate the forest canopy, and therefore reliable positions can be obtained using proper procedures and equipment. GPS positioning is dependent on the GPS receiver collecting and processing a usable signal from a minimum of three two-dimensional (2-D) or four three-dimensional (3-D) GPS satellites. At this time there are 26 operational satellites in orbit for use with GPS surveys. A reference receiver is required to collect positioning data simultaneously at a known location within 100-150 miles of the field position. Data collected from the fixed GPS receiver and positions collected by a roving GPS receiver allow post-processing to obtain differential GPS/DGPS positions which are more precise than those obtained using a single receiver.

Mapping grade GPS receivers are commonly only single frequency (L1) GPS receivers. These units receive only the course acquisition (C/A) code and are capable of computing the post-processed DGPS position to an accuracy within 2 to 5 m X-Y, and 4 to 10 m Z, or elevation. GPS receivers require a relatively unobstructed view of the sky (i.e. GPS satellites).

Many locations within a BLH forest are suitable for GPS reception using mapping grade receivers; however, the time spent at these locations is dependent upon good planning and proper field techniques which allow a suitable number of position observations to be recorded with the satellites. Most receivers can provide coordinate display for monitoring position and system performance as well as the total number of observations collected for a group point.

GPS PROCEDURES: A GPS demonstration project was conducted within the Cache River Basin, AR, to determine the position of sediment stations adjacent to a flagged transect line, to determine the azimuth of that line, and to record the relationship of established sampling sites for mammal, soils, vegetation, and sediment stations along each transect line. The transect was originally laid out with a compass and tape (Fig. 1), and trees were tagged every 60 m along the line.

In order to conduct a proper DGPS survey, several U.S. Geological Survey (USGS) control points were located within a 35-km radius of the area. These marks had published latitude, longitude, and elevation available. The WES field team deployed the 12 channel GPS reference receiver on a control point at the local airport for use during GPS data collection periods.

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An L1, C/A code, 6 channel roving receiver was used for surveying the XY positions. The receiver was equipped with an external antenna, 10-m antenna cable, extendable range pole, and a data recorder capable of recording positions both as points, or as point features, allowing names and notes to be entered about each.

The receiver was set to the manufacturers recommendations concerning satellite elevation, Positional Dilution of Precision (PDOP), and 2-D/3-D mode switching. The L1 roving receiver was deployed and immediately began receiving information from six satellites, using the best four satellites for determining the current coordinate position. As field personnel entered the forest, where the tree foliage and branching interrupted some signals (Fig. 2), the unit began receiving signals from as few as three satellites while continuing to compute positions. As the team walked along the flagged path, points were recorded by computing positions every three seconds. An audible beep would sound as each ground position was logged. The receiver was allowed to automatically switch to the best combination of satellites to assure the tracking and recording of the best positions. The antenna was carried atop a 2-m extendable pole, and the pole held such that the antenna's orientation would allow signals to be received on the flat antenna plate inside the top cover. When satellite signal reception was interrupted due to dense foliage and heavy branching, the field party would pause or move slowly along the line until signal reception and recording was reobtained. The team collected both 2-D and 3-D satellite position data.

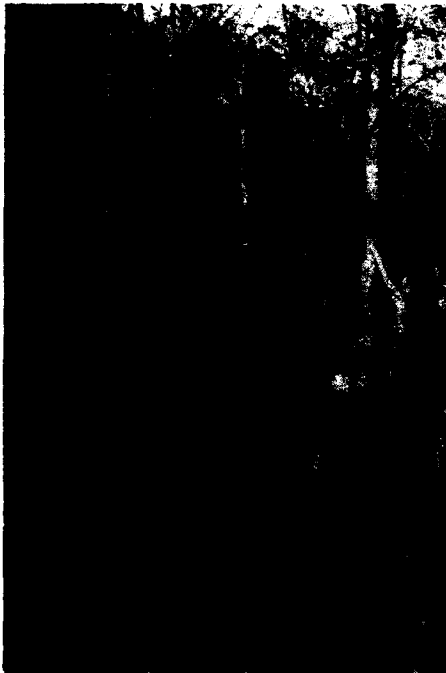


Figure 1. Location of transect line



Figure 2. Foliage and branching structure

Four different transect lines were previously established within the Cache River forested wetland, each about 2 km in length. The DGPS survey results of one line, transect "C", are shown graphically in Figure 3. Figure 3a shows the 2079 corrected 2-D positions (3 satellites), plotted to determine the azimuth/orientation of the transect line. Figure 3b shows the line using 2094 corrected 3-D points (4 satellites). Figure 3c is a plot of 2-D and 3-D data used together (4173 points). If the best line is defined by calculating the mean, the deviation of the points from the calculated line was only 2-6 m, except for a few "extreme" 2-D points. After manual editing of the 2-D and 3-D data points, the resulting line was defined and is shown in Figure 4a. There was little accuracy advantage to using 3-D data alone, as the majority of the 2-D points were equally as reliable.

The positions of sediment sampling sites located adjacent to the transect line in the BLH forest were determined by acquiring GPS positions at stationary locations for three minutes, collecting data once per second. Again both 2-D and 3-D data were collected. The observations recorded at these seven sampling sites were later processed as group points, to determine the mean, and standard deviation for each site surveyed. These data are displayed in Figure 4b. The overall accuracy of an individual sampling site location (XY coordinate) was considered to be improved using this technique. The computed transect line with the mean position of the seven sediment sites is displayed in Figure 4c.

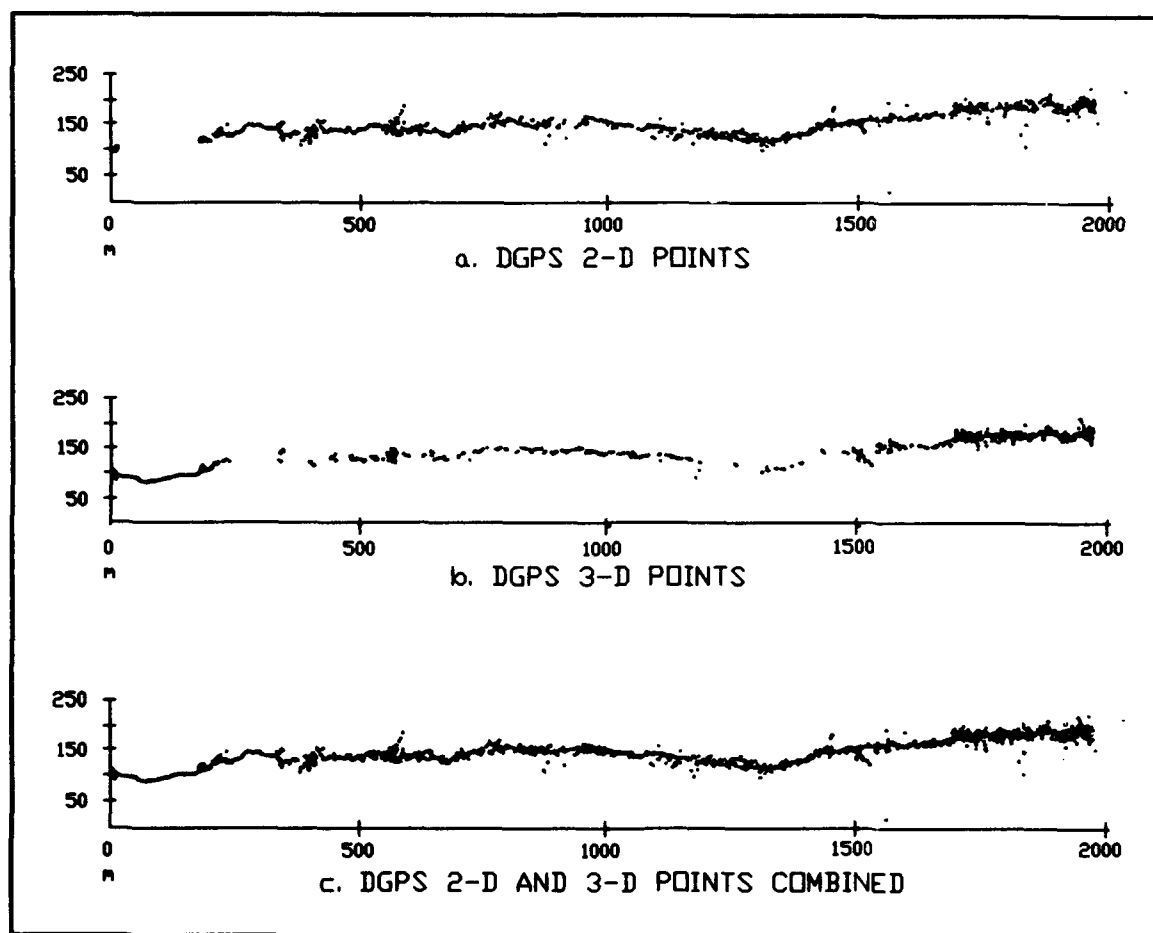


Figure 3. Raw DGPS data within the Cache River BLH forest

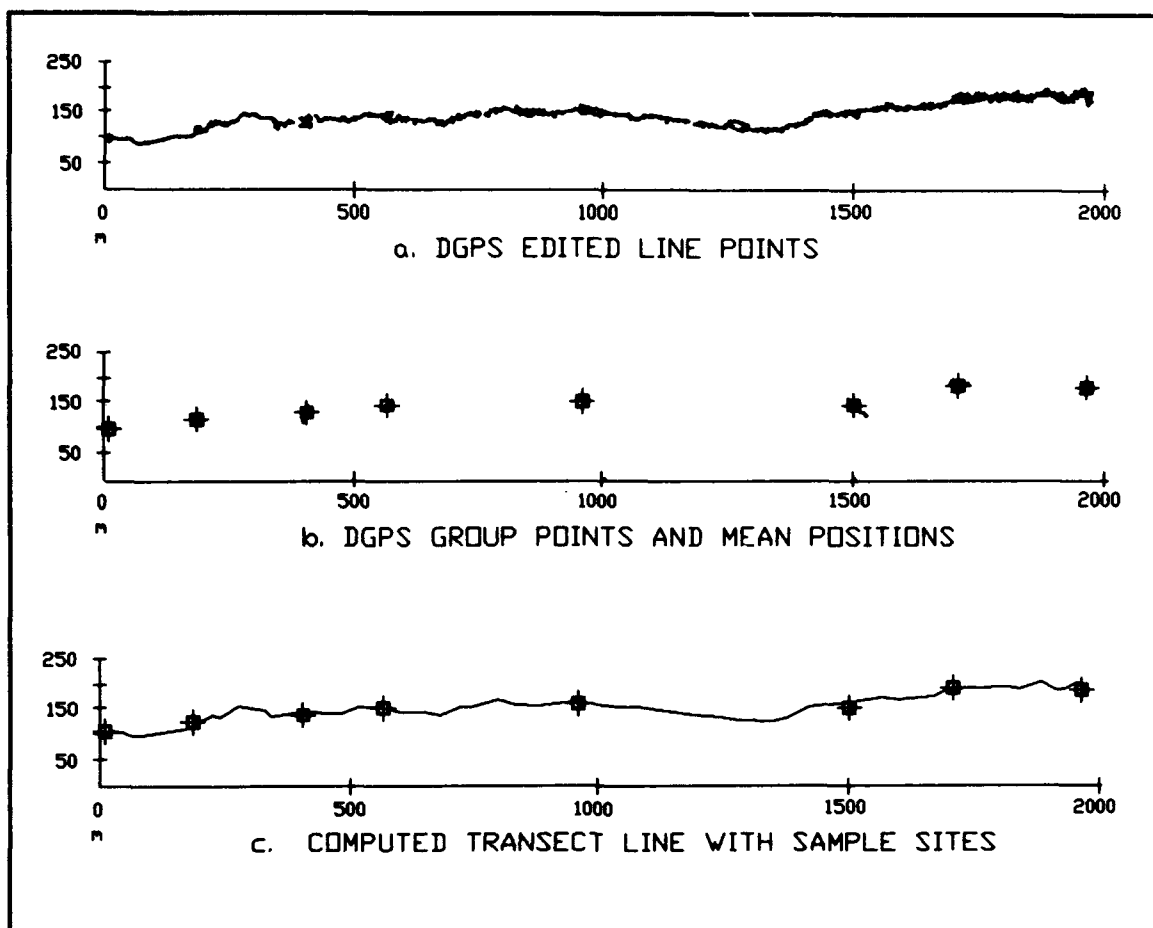


Figure 4. Edited DGPS data within the Cache River BLH forest

The sediment sites were located accurately with respect to the transect line as shown in Figure 4c. These reduced and edited transect line data are now suitable for transfer to a Geographic Information System (GIS) database system such as the one available for the Cache River Basin.

Elevation data (Z coordinates) could not be reliably obtained using DGPS techniques and as a result standard survey procedures were used to determine the elevation of the sediment sites.

CONCLUSIONS: GPS XY coordinate positions were obtained within a BLH forested wetland to an accuracy of approximately 2-6 m. However, GPS position data are best obtained by using the stationary site (group point) method, such as used for the sediment sites. A transect line is best defined by locating GPS positions or points every 50-75 m along the line.

If elevations within a BLH forest are required, monumented control points should be established by static DGPS methods outside the forest, at the beginning of each transect, and then the elevations transferred along the transect using traditional leveling techniques.

ADDITIONAL INFORMATION SOURCES:

USACE. 1991. NAVSTAR Global Positioning System Surveying. Engineer Manual EM 1110-1-1003. Washington, DC.

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Trimble Navigation. 1991. TRIMVEC-PLUS® GPS Survey Software, User's Manual and Technical Reference Guide. Part Number 12351. Sunnyvale, CA: Trimble Navigation Ltd.

Trimble Navigation. 1992. General Reference, GPS Pathfinder® System. Part Number 18470-00. Sunnyvale, CA: Trimble Navigation Ltd.

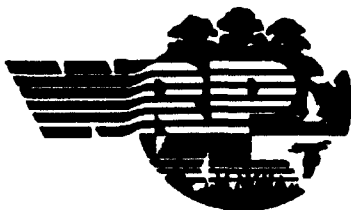
Trimble Navigation. 1991. PFINDER® Software User's Guide. Part Number 18473-00. Sunnyvale, CA: Trimble Navigation Ltd.

ADDITIONAL INFORMATION ON GPS:

The U.S. Army Topographic Engineering Center (TEC), Fort Belvoir, Va. is conducting research on GPS methods/procedures, and additional information and list of publications may be obtained by contacting: Mr. Steven R. DeLoach, ATTN: CETEC-TL-SP, Fort Belvoir, VA 22060-5546. Phone (703) 355-3026.

Also, Office, Chief of Engineers, Directorate of Civil Works provides information of use of GPS Technologies to support broad mission areas. Point of contact is Moody K. Miles, III, ATTN: CECW-EP-S, Washington, DC. Phone (202) 272-8885.

POINT OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Thomas E. Berry, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-EN-C, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601) 634-3927, author.



Hyperspectral Imagery: A New Tool For Wetlands Monitoring/Analyses

PURPOSE: This technical note describes the spectral and spatial characteristics of hyperspectral data and the potential application of these data for wetlands studies and monitoring applications. The advantages and disadvantages of these data for wetland evaluations are discussed. Spectral signatures extracted from data acquired by NASA's collected Airborne Visible/Infrared Imagery Spectrometer (AVIRIS) hyperspectral scanning over a wetland study site are analyzed.

BACKGROUND: Remote sensing technology is an important tool for exploring, monitoring, and analyzing wetland systems. Researchers have explored the use of digital imagery acquired from aircraft and spaceborne platforms for mapping wetlands and for analyzing changes to wetland systems (Lampman, 1992). However, traditional digital imagery from multispectral scanners is subject to limitations of spatial and spectral resolution.

- Spatial resolution refers to the size of individual picture elements or the area of the surface imaged in each of the square elements which compose the image. Spatial resolution is usually measured in meters. Typically, sensors such as the Thematic Mapper (TM) carried on the Landsat series of satellites have a spatial resolution of approximately 30 by 30 m. In other words, a feature must be fairly large and homogenous in nature in order to be detectable in an image.
- Spectral resolution refers to the number and width of the portions of the electromagnetic spectrum measured by a sensor. Multispectral scanners measure the radiation reflected by surface features in several portions of the spectrum and convert these analog measurements into digital counts, usually representing an 8-bit (0-255) range. By using statistical methods to analyze the distinct way in which different surface features reflect radiation in different parts of the spectrum, it is possible to characterize the surface features which make up an area. When the radiation reflected by a surface feature is only measured in 4-10 broad portions of the spectrum (which is typical of traditional multispectral sensors), it is sometimes difficult to differentiate between surface cover types which are similar in nature (such as wetland flora), or to detect subtle changes in the cover types of interest. The broad nature of the spectral wavebands acts to mask the subtle differences in spectral response of like cover types. When the spectral and spatial limitations of multispectral scanners are considered in concert, one can begin to appreciate the difficulties in using data from these sensors for mapping and analyzing areas as complex as wetlands.

A new type of remote sensing scanner is now being produced which, unlike multispectral scanners, is capable of measuring up to 250 very narrow portions of the spectrum. The systems are referred to as "hyperspectral sensors." They promise to revolutionize the utility of remotely sensed data for mapping and monitoring wetlands by eliminating the prior limitations of spectral resolution. With hyperspectral sensors it may be possible to map individual wetland plant species, as well as to detect very subtle changes in wetland systems, such as early signs of stress. Despite the great promise they offer, these sensors also introduce a suite of problems which must be addressed before it will be possible to routinely use these data for wetland applications.

Hyperspectral scanners collect large amounts of data, even when imaging a relatively small area at a coarse spatial resolution. For example, if the spatial resolution of a hyperspectral image is 20 by 20 m, and an area of 10,000 by 10,000 m is imaged, the resulting data requires approximately 150 megabytes of disk storage space. The same area imaged with a 2-m effective resolution would yield an image 11 gigabytes in size. Each 20 by 20 m image pixel in the above example would have approximately 220 associated spectral values. The volume of data makes it difficult to extract useful information. Statistical analysis techniques commonly used to process multispectral data are not suited to the amount and dimensionality of data present in a hyperspectral image. The problems encountered in processing hyperspectral data are, in some ways, similar to those experienced in the 1960s with the advent of multispectral data. The volume of data and the CPU-intensive algorithms which were required to extract information from multispectral data presented a challenge to computers of the time. Likewise, the amount of data collected by hyperspectral sensors represents a challenge to today's vastly improved computers.

AVIRIS APPLICATION: To examine the potential future applicability of hyperspectral techniques for monitoring wetlands, an image obtained from the AVIRIS hyperspectral scanner was acquired over an area adjacent to Green Bay, WI. The spectral curves measured over three different wetland types were examined. By viewing the high resolution spectral curves measured by the sensor over similar cover types in concert, it was possible to determine whether or not hyperspectral scanners like AVIRIS offer promise as future tools for routinely monitoring wetlands.

- **Study area.** The Green Bay West Shores State Wildlife Area is located along the southwest corner of Green Bay. The principal study site was a small coastal wetland area just north of Green Bay, WI (Figure 1). Three different wetland types were selected from 1:24000 scale Wisconsin Wetlands Inventory (WWI) maps. The three wetland types chosen were: Emergent/wet meadow, narrow-leaved persistent, wet soil (E2K); forested, broad-leaved deciduous, wet soil (T3K); and scrub/shrub, broad-leaved deciduous, wet soil (S3K).
- **The AVIRIS scanner:** The AVIRIS scanner is an airborne precursor to the High Resolution Imaging Spectrometer (HIRIS), which NASA plans to launch into space as a component of the Earth Observation System (EOS) in the future. The EOS represents a part of NASA's Mission to Planet Earth initiative (Gao et al., 1993, Goetz et al., 1985). AVIRIS was developed to enable the scientific community to conduct investigations into the utility of hyperspectral scanners for applications prior to the launch of the HIRIS. By making AVIRIS data available to scientists in a wide range of fields, it is hoped that the development of data utilization methodologies will be hastened so that hyperspectral data from the spaceborne platform will be employed more effectively. The Jet Propulsion Laboratory (JPL) is responsible for maintaining and operating AVIRIS until the HIRIS is in orbit.
- **WRP study.** A four step approach was taken to perform an initial investigation into AVIRIS data and to determine if it could be used to delineate different wetlands types. These steps required a basic knowledge of image processing techniques to extract useful information from the data.

First, the AVIRIS data were loaded from the source tape provided by NASA's Jet Propulsion Laboratory onto a workstation class computer. The imagery acquired over the study area required 145 MB of disk space and was composed of 224 spectral channels, with 16 bit, signed (including negative) values. The image processing software at the WES Environmental Laboratory could display, but not process, 16-bit, signed data. Therefore, it was necessary to rescale the data values into an 8-bit, unsigned range (0-255). The maximum number of channels handled simultaneously by most commercial software packages is 15 to 20. As a result of this limitation,

it was necessary to divide the AVIRIS data into separate image files prior to processing.

The second step in processing the imagery was to georeference these data to a common base map (Fig. 1). When aircraft data are collected, the data are not referenced to any coordinate system, or map base; therefore, before an evaluation of the data's usefulness could be conducted, the data had to be referenced to some real world map projection. This allowed overlay vector data from the Wisconsin Wetland Inventory, which had been digitized into a geographic information system (GIS), to be overlaid onto the imagery. Data georeferencing was performed by locating identifiable ground control points which were visible on both the AVIRIS data and 1:24000 scale quad maps, and then resampling the image data using a cubic two-dimensional polynomial algorithm.

The third step consisted of extracting spectral signatures for three different wetland types from the AVIRIS data. The areas of interest were defined by overlaying the Wisconsin Wetland Inventory vector data on the AVIRIS image and extracting homogeneous pixels for each of the different polygon types. Four by four pixels blocks were then extracted from within the center of the polygon boundaries to insure that the pixels showed little or no variation in reflectance values and to insure that pixels selected were indeed the correct wetland type. Without taking this precaution, pixels along the polygon boundaries could inadvertently be selected. These boundary pixels could possibly have been indicative of a different wetland type or the result of a "mixed-pixel" effect. The sample extraction areas were then converted to vector format so that data could be extracted from the same areas for each of the 16-channel image files. In the fourth step, image statistics were generated for each of the three wetland types for all 224 channels, resulting in the spectral signatures presented in Figure 2.

- Preliminary results. At first glance, it appears that the three spectral curves presented in Figure 2 are quite similar. In a normal multispectral image, these three cover types would be almost impossible to distinguish, as the small differences which exist in certain portions of the spectrum would be masked by averaging effects. However, with the proper selection of bands (particularly in the near-infrared portion of the spectrum) and the appropriate algorithms, it should be possible to routinely delineate the three cover types of interest using hyperspectral data. These preliminary results indicate that phenological differences between even very similar wetland plant types can be effectively detected with hyperspectral data, but highlight the need for additional research into the use of hyperspectral data for monitoring wetlands.

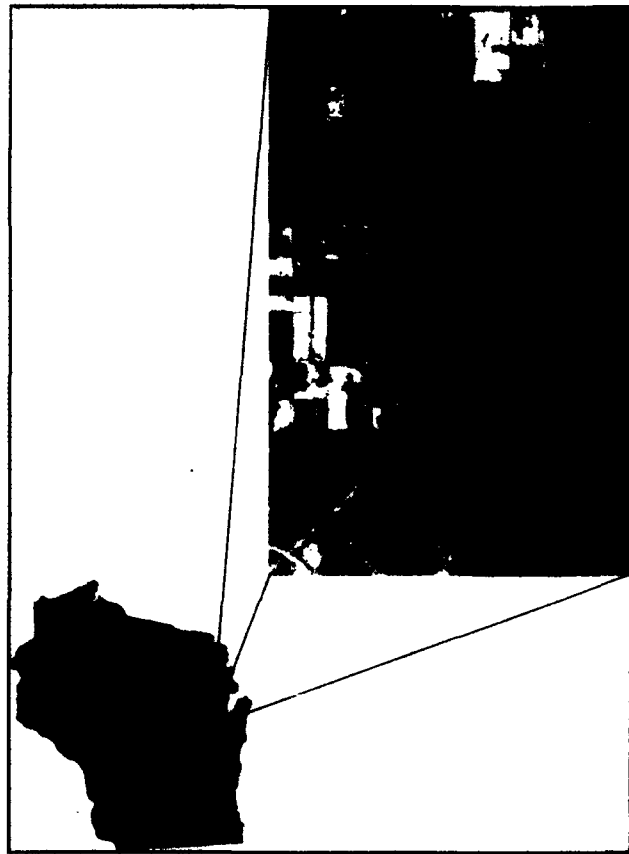


Figure 1. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Data Acquired of the Green Bay, WI Area

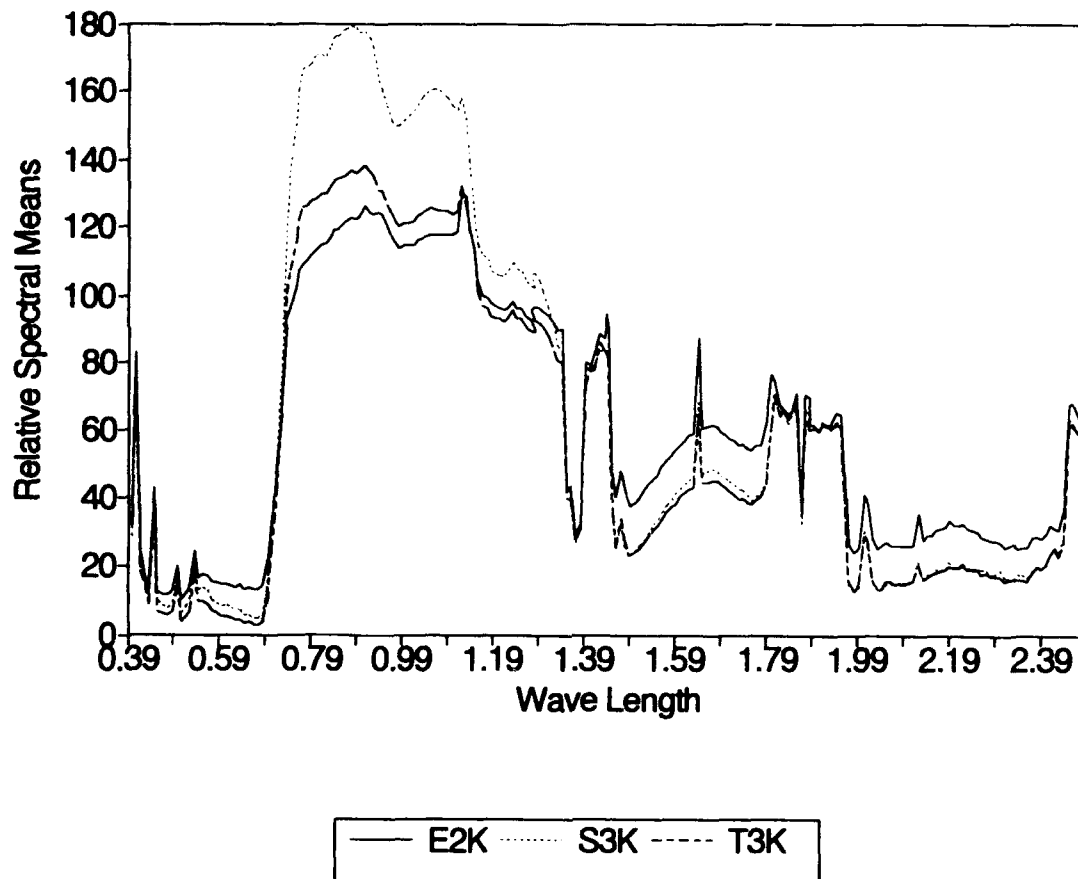


Figure 2. Spectral Means of the Three Wetlands Types

FUTURE DEVELOPMENT: Most of the limitations in using hyperspectral data arise, not from the data itself, but from the current state of the art in processing capability and knowledge of the spectral characteristics of the features of interest. For example, in order to be able to routinely distinguish between similar cover types, it is necessary to have a good understanding of the spectral characteristics of the cover types of interest. The Corps of Engineer's Topographic Engineering Center (TEC), as well as other facilities, are currently conducting "greenhouse" experiments where the spectral signatures of surface cover types are being catalogued in "signature banks." These signature banks will allow researchers to be selective in terms of the channels they select to process out the set of available wavebands. This will reduce the need to process so many channels of data concurrently and limit the size of the image files to be processed. Signature banks could also be used in the future for developing automated techniques for processing hyperspectral imagery. Computers could examine the spectral signatures from all 200 or so spectral channels, compare them to the a huge signature bank, and make accurate decisions as to the composition of the imaged area. This type of analysis is already being conducted in the western United States for geological mapping applications, as the spectral signatures of rocks and minerals are much easier to catalog and are static in nature as opposed to vegetation.

Another limitation of hyperspectral data at this point is the cost of data from hyperspectral platforms. Very few hyperspectral sensors currently exist and data from these sensors are extremely costly. It is

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also very difficult to schedule overflights from these sensors as they are currently oversubscribed. This limits the usefulness of hyperspectral data at this time; however, with the launch of the HIRIS system, towards the end of this decade, these limitations will no longer apply. It is incumbent on the wetlands research community to encourage further, much more detailed, investigations into the utility of these data for monitoring our wetland resources so that, once data from spaceborne platforms are available, the data may be fully exploited for wetland applications.

FOR MORE INFORMATION CONCERNING THE USE OF HYPERSPECTRAL DATA WITHIN THE CORPS: The Corps of Engineers has establish a Remote Sensing/GIS Support Center to assist in the application of remote sensing technologies. The address is:

U.S. Army Cold Regions Research & Engineering Center
ATTN: Remote Sensing/GIS Support Center (CECRL-RSGISC)/Dr. H. McKim
72 Lyme Road
Hanover, NH 03755-1290
(603)646-4372

Also, the U.S. Army Topographic Engineering Center (TEC), Fort Belvoir, VA, is conducting research on use of Hyperspectral Data and additional information can be obtained by contacting:

U.S. Army Topographic Engineering Center
ATTN: Dr. Jack Rinker
Fort Belvoir, VA 22060-5546

POINTS OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Mark Graves, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-EN-C, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601)634-2557.

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NOTE: Some titles are abbreviated

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